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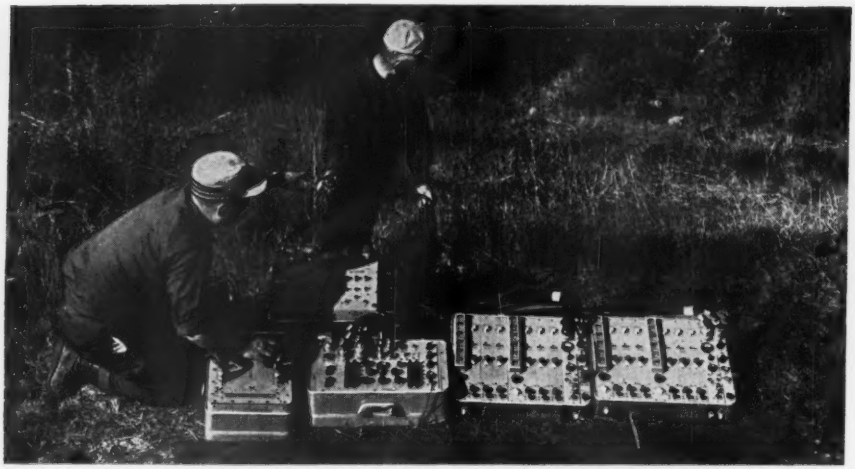

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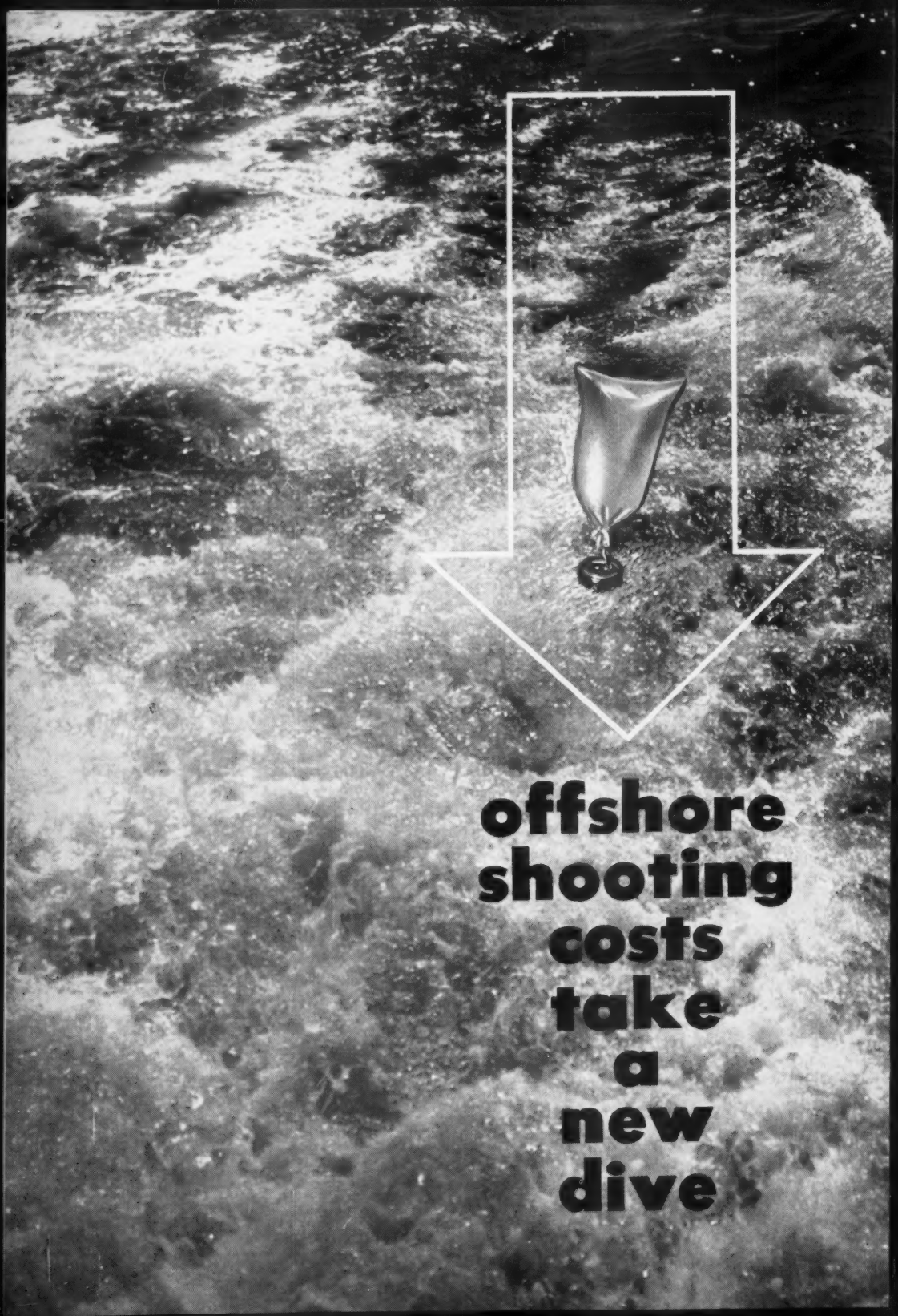
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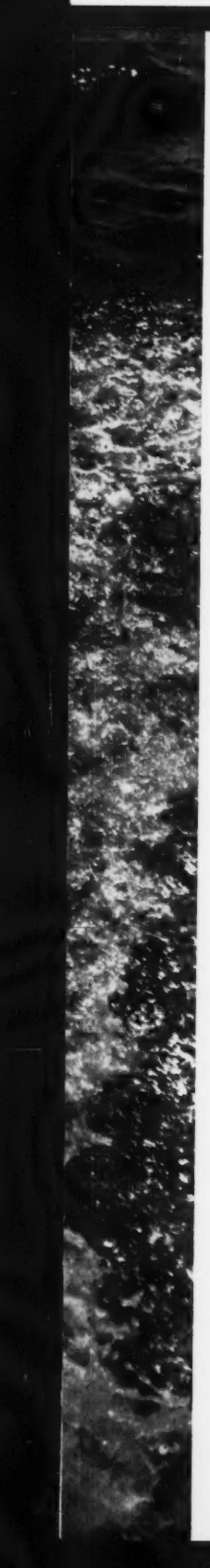

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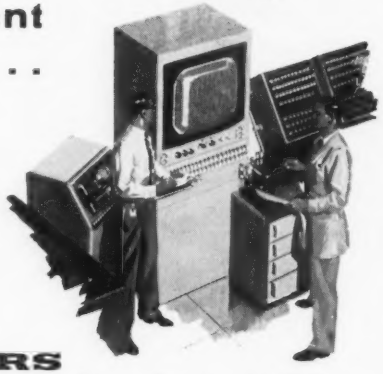

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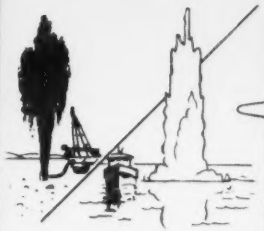

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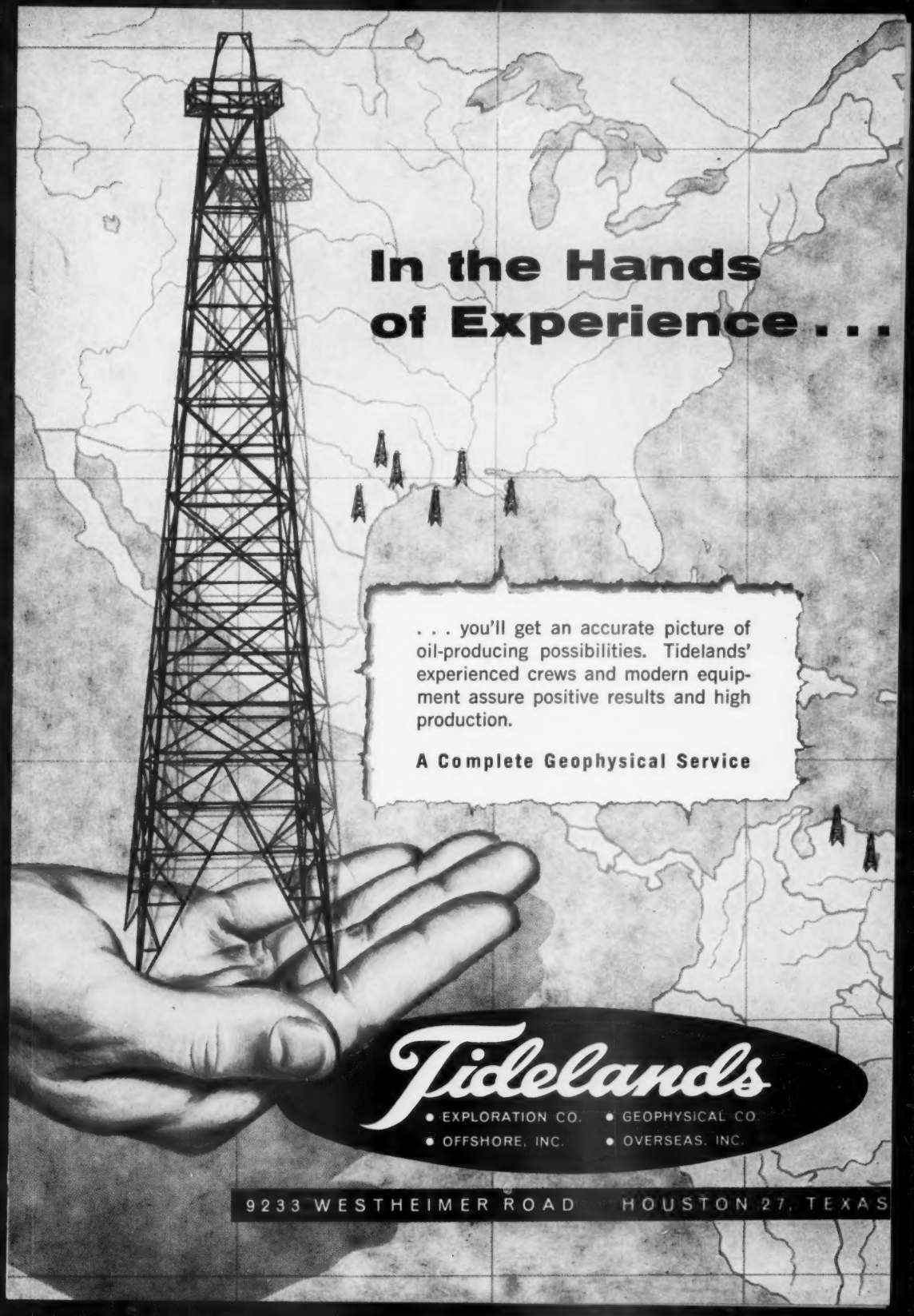
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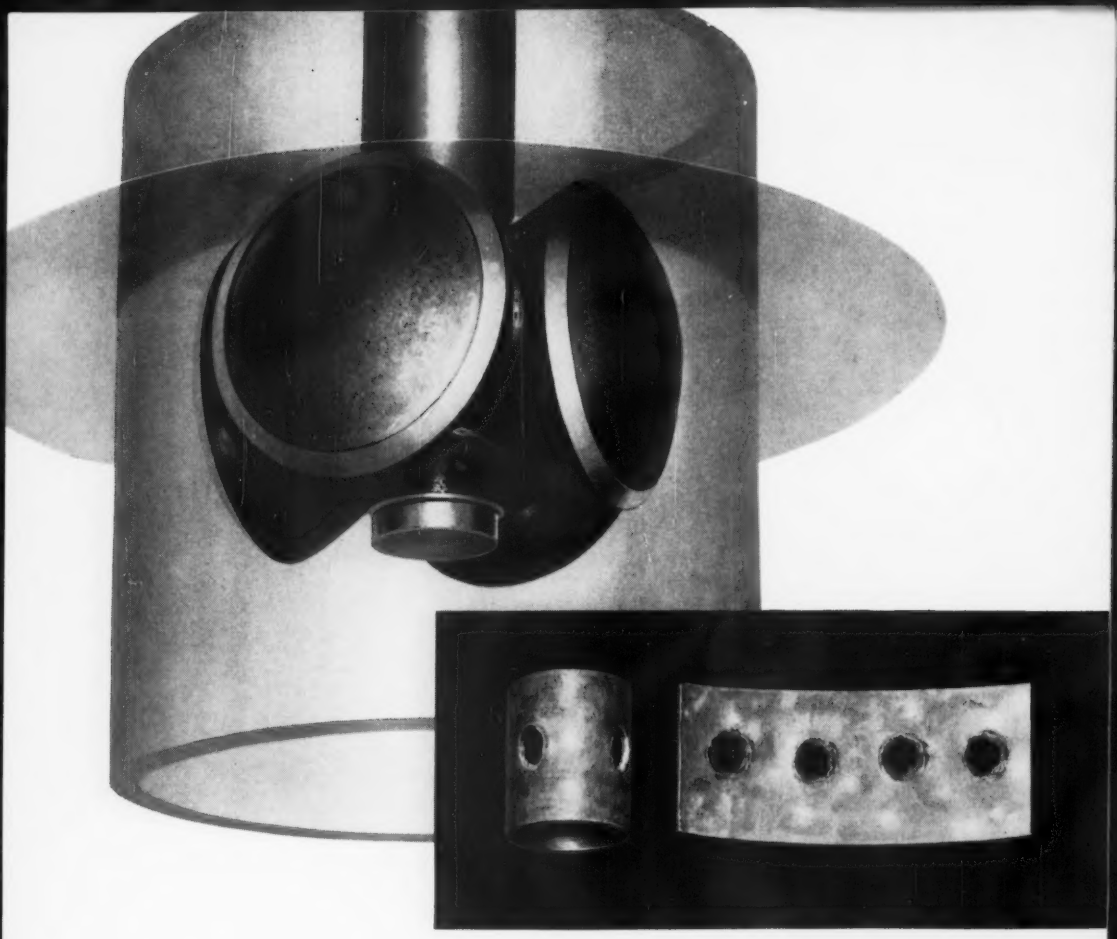

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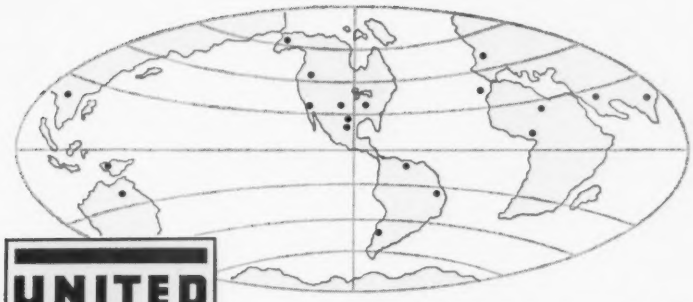

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ELIMINATION OF SECONDARY PRESSURE PULSES IN OFFSHORE EXPLORATION*

WILLIAM C. KNUDSEN†

Abstract: The behavior of a gas bubble generated by detonating an explosive below the surface of the ocean and located centrally in a perforated sphere, perforated pipe, and solid-walled pipe has been studied by means of a scale model. The motion of the bubble was recorded using a high speed camera, and the pressure variations were recorded using a small pressure detector. The behavior of the gas bubble when surrounded by a perforated sphere has also been analyzed numerically. The model results showed that significant reduction in secondary pressure pulse amplitude was effected by all three devices, but the perforated sphere was the most effective. That enclosing the gas bubble in a perforated sphere would effectively eliminate the secondary pressure pulses was also verified by the numerical solution of the motion. Design criteria for a perforated sphere are presented.

LIST OF SYMBOLS

a	radius of gas bubble
$\bar{a}$	minimum radius of bubble at end of first period
A,B,C	differential equation coefficients ($=\gamma/2R^4$, gz, $kW^{1.23}/\rho$)
b	thickness of envelope
D	density of fluid
$E(a)$	internal energy of the gas
F	fraction of total explosive energy
γ	coefficient of pressure drop across screen
g	acceleration of gravity
k	gas pressure constant
$\hat{k}$	constant unit vector along a radius
μ	water viscosity
p	pressure
P_a	gas pressure
P_0	hydrostatic pressure at charge depth
P_1	water pressure adjacent to inside of perforated sphere
P_2	water pressure adjacent to outside of perforated sphere
ρ	water density
Q	energy of explosive per unit weight
r	radial distance from charge center
R	radius of perforated sphere
R_1	ratio of peak pressure of secondary pressure pulse with and without sphere
R_2	ratio of energy radiated in secondary pressure pulse with and without sphere
S	ratio of solid area to total area of sphere
s	effective, meridional, membrane stress
$\overline{d\sigma}$	directed surface element
t	time
u	radial water velocity
V	volume
W	weight of explosive
z	length determining hydrostatic pressure

INTRODUCTION

In a previous paper I reported model experiments conducted to study the motion of gas bubbles generated by explosives detonated in large bodies of water (Knudsen, 1958). Specifically, the experiments were conducted to determine the effectiveness of various techniques and devices which had been proposed in the patent literature for reducing the amplitude of the secondary pressure pulses. The experimental results showed that those proposed techniques which would permit detonating a reasonably sized charge at depths

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† California Research Corporation, La Habra, California.

greater than about 20 ft were not promising. Model experiments conducted to determine the effectiveness of bubble oscillation suppressing devices suggested by the previous study are reported here.

One benefit to seismic exploration which may be derived from exploding the source at a greater depth below the surface than the conventional 5 ft is suppression of undesired modes of wave propagation. The response of a system to a source depends on the location of the source as well as on the strength and frequency spectrum of the source. For example, the strength of the normal modes of wave propagation in a two-layered liquid model depend on the depth of the source (Knudsen, 1957). The second mode can be suppressed relative to the first mode by locating the source at a depth equal to two-thirds the total water depth. The "singing" disturbance which makes reflection seismology interpretation difficult or impossible in some water covered areas may possibly be suppressed relative to the desired signal by locating the charge at the appropriate depth (Werth et al, 1959; Backus, 1959). Another possible benefit from shooting at greater depth is larger seismic amplitude from the same charge weight.

The bubble motion generated by detonating an explosive charge in water several bubble radii from the nearest fluid boundary, such as the ocean floor or surface, is as follows. After radiation of the initial shock wave, approximately one-half of the total energy of the charge remains in the form of internal energy of the gaseous explosion products and kinetic energy of the outwardly flowing water. The gases are contained in a spherical bubble which expands as the water flows radially outward. As the bubble expands, the internal energy of gases is converted to kinetic energy of the outwardly flowing water and potential energy of the bubble cavity. The pressure of the gases decreases rapidly as the radius increases and falls below the hydrostatic pressure at the depth of the charge. Consequently, the outward flow of water is decelerated and ultimately stopped. At this maximum bubble radius, the energy of oscillation is almost entirely in the form of potential energy. The bubble then contracts, and the energy of oscillation is converted back into internal energy of the gases and kinetic energy of the moving water. At the instant of minimum bubble radius, the energy of oscillation is contained in the form of internal energy of the gases. (For the moment, losses of oscillation energy which occur during the minimum radius phase of the oscillation are ignored.) The oscillation cycle is then repeated.

During the short time interval when the internal energy of the gases is large, the pressure in the gases is very high, and a significant fraction of the energy of oscillation is radiated away from the bubble in the form of an acoustic wave or secondary pressure pulse. The secondary pressure pulses are generated at intervals of a few tenths of seconds after the initial shock wave for charge sizes normally used in seismic exploration and for charge depths within a few hundred feet of the surface. Occurring as they do a few tenths of seconds after the initial shock wave, the secondary pressure pulses and their seismic disturbances are recorded together with the desired seismic disturbance generated by the initial shock wave and prevent proper interpretation of the subsurface geology (Lay, 1945; Chujo, 1958).

The current technique for avoiding the disturbance caused by the secondary pressure pulse is to explode the charge within approximately 5 ft of the water surface (Ewing et al, 1946; Lay, 1945). When the charge is exploded at greater depths, the secondary pressure pulses are usually observed. Ewing et al (1946) reported that 87 percent of the shots fired at mid-depth in the ocean produced one or more secondary pulses and that 63 percent of the shots fired on bottom produced one bubble pulse. Worzel and Ewing (1948) reported that a majority of the shots fired on bottom produced one bubble pulse, and a majority of the mid-depth shots produced two or more pulses. It has been observed that secondary pressure pulses are observed when the charge is fired in soft mud (Chujo, 1958; Lay, 1945). The periods of the secondary pressure pulses are consistent with the assumption that the bubble motion is identical to that in water. It is only necessary to correct for the increased density of the fluid. These experiences, together with the results of the previously reported model experiments, demonstrate the stability of the bubble motion.

It is apparent that, to eliminate the secondary pressure pulses, the energy of oscillation must be dissipated or converted into some form of nonconservative fluid flow during the first expansion and early part of the first contraction. This accomplished, little energy would be available to

compress the gases. In Appendix I, approximate theories of the secondary pressure pulse reported by Cole (1948, p. 353) are rewritten to show that the peak pressure and the energy radiated depend rather strongly on the amount of internal energy of gases at the instant of minimum bubble radius. Hence, promising techniques for reducing the seismic disturbance of secondary pressure pulses must reduce significantly the energy returned to the gases as internal energy.

Not all of the energy of bubble oscillation is returned to the gases in the unobstructed bubble oscillation. During a small time interval centered about the time of maximum contraction, the bubble acquires a significant vertical velocity. Some of the oscillation energy goes into the kinetic energy of this motion. Also during this time interval, part of the energy of oscillation is radiated as the secondary pressure pulse and part dissipated in turbulence associated with the vertical motion of the bubble. Cole (1948, pp. 374–379) reports that measurements on bubble periods show that about two-thirds of the bubble oscillation energy is lost each cycle and is accounted for primarily by turbulence and the secondary pressure pulse. Although these mechanisms dissipate bubble oscillation energy, they do so too late. Appreciable energy must be dissipated prior to the contraction of the bubble into a small volume.

MODELING TECHNIQUE

An explosion at depth in the ocean was modeled as follows. The ocean was simulated with clear oil contained in a vacuum tank. A chemical explosion was simulated by discharging a condenser across a spark gap. Motion of the gas bubble was photographed using a high speed camera and a Schlieren lighting arrangement. The secondary pressure waves radiated by the bubble motion were recorded using a pressure detector.

It is necessary in all model experiments to investigate how reliably the model represents the prototype. The model will reliably represent the prototype provided that all independent, dimensionless parameters which can be formed from the significant physical variables have the same value for both prototype and model. The fluid of the model and prototype may be considered incompressible during the bubble motion except for a small time interval centered on the time of minimum radius. The significant dimensionless parameters pertinent to the "incompressible" flow of the fluid had the same value in both model and prototype with the exception of a Reynolds number, $2\,ua\rho/\mu$ (Knudsen, 1958, p. 457). The Reynolds number for the model was approximately 2×10^4 whereas that for a prototype would be 8×10^7. The large value for both model and prototype implies that dynamic (inertia) forces are predominant over viscous forces throughout most of the fluid volume (Sommerfeld, 1950, p. 113). Only in a thin layer adjacent to a solid surface, such as that of an elimination device, does the viscosity play a significant role. The behavior of the model bubble surface adjacent to the spark gap electrodes verifies this last statement (Knudsen, 1958, Figures 1, 5, 6, 7, 8, and 9). The larger Reynolds number of the prototype suggests that turbulence might set in more readily in the prototype than in the model.

During the time of minimum bubble radius, the compressibility of the fluid becomes significant (Cole, 1948, p. 353). To properly model this phase of the bubble motion, the sound velocity of the model fluid should have been smaller by an order of magnitude than it actually was (Knudsen, 1958, p. 458). The consequence of a too large value is a too small total amount of acoustic energy radiated in the form of a secondary pressure pulse (Cole, 1948, p. 377). Since the peak pressure does not depend significantly on the compressibility of the fluid and was properly modeled, the secondary pressure pulses produced by the model are expected to be narrower in time and richer in high frequencies than the properly modeled pulses.

The effectiveness of an oscillation suppressing device was judged by comparing the behavior of the bubble motion and the amplitude of the secondary pressure pulse with the device in place with the behavior of the motion and amplitude of the pulse with no device in place. As pointed out above, the peak gas pressure attained during the contraction of the bubble does not depend too strongly on the compressibility of the fluid. Hence, the recorded peak pressures should be representative of the prototype to the extent that the incompressible motion of the prototype was properly modeled. The secondary pressure pulses were recorded broadband to record the maximum peak pressure attained during contraction. The modeled secondary pressure pulses were also recorded after filtering with a model band pass equivalent to that of conventional seismic record-

ing equipment. The amplitude of the filtered pulse was a measure of the effectiveness of a suppression device in reducing the amplitude of the low frequency components of the secondary pressure pulse.

Additional details on the experimental techniques used are given in the previous paper (Knudsen, 1958).

EXPERIMENTAL RESULTS

To suppress the amplitude of secondary pressure pulses, considerable bubble oscillation energy must be dissipated prior to the first collapse of the bubble. Once this was realized, several devices for dissipating the energy came to mind (Knudsen, 1956).

The three most promising techniques of those tested are reported here. In each experiment the charge was equivalent to approximately 15 pounds of TNT and was at an equivalent depth of 75 ft.

A positive method of dissipating energy is to surround the charge with a perforated sphere. As the bubble expands, water is forced through the sphere. A pressure difference will exist across the sphere as a result of this flow, and work will be done in forcing the water across this pressure difference. The total energy dissipated during the first cycle may be expressed as

$$\text{work} = \int_{V_0}^{V_{\max}} (P_1 - P_2)dV + \int_{V_{\max}}^{V_{\min}} (P_1 - P_2)dV$$

where (P_1-P_2) is the instantaneous pressure difference across the sphere; V_0, the initial volume of the bubble; $V_{\max}$, the maximum bubble volume attained; and $V_{\min}$, the minimum volume of the bubble reached at the end of the first cycle. (P_1-P_2) changes sign upon change in direction of water velocity so that energy is dissipated during the expansion and contraction.

To investigate this method of eliminating the secondary pressure pulses, 100-mesh wire gauze (100 wires per inch) was formed in the shape of a sphere and placed in the model tank. The radius of the sphere is equivalent to eight feet, but is larger than proved necessary. The bubble motion is illustrated in the sequence of pictures shown in Figure 1. Time increases left to right and from top to bottom for this figure as well as for Figures 2 and 3. Successive pictures do not represent equal time increments. The spark gap rods extend into the sphere through a slit on the right. The sphere is supported at the left. The gas that can be seen emerging from the top of the sphere beginning in frame 3 is gas trapped in the top of the sphere from a previous explosion which is being forced out by the expansion of the current explosion. Notice that the sphere is distorted toward the right as a result of the pressure difference developed across it. The pressure amplitude results registered by the pressure detector are given in Table I for this experiment and for an identical experiment, with the exception that a 200-mesh sphere was used.

A method suggested by a colleague, R. I. Maddox, consists of locating the charge in an open ended pipe. The idea is that ring vortices will be formed at the ends of the cylinder, where surfaces of velocity discontinuity occur, and that these vortices will carry off some of the bubble oscillation energy. Figure 2 shows a sequence of pictures illustrating the behavior of the gases from the equivalent of a 15-pound charge detonated in a pipe 3 ft in diameter and 12 ft long. The behavior of the gas bubbles strongly suggests the existence of a ring vortex. The pressure results for this method are given in Table I.

A third method consists of locating a charge in a perforated pipe. Energy would be dissipated by the movement of water through the perforations and by the ring vortices formed at the ends of the pipes. Figure 3 illustrates the bubble motion when the equivalent of a 15-pound charge is fired in a cylinder 10 ft long and 5 ft in diameter. Again ring vortices are formed, and some fluid is forced through the walls of the cylinder. The pressure results for this case are contained in Table I.

DISCUSSION OF EXPERIMENTAL RESULTS

The results shown in Figures 1, 2, and 3 and in Table I demonstrate that considerable reduction of the secondary pressure pulses can be effected by detonating an explosive in one of the devices described. Table I illustrates that the 200-mesh sphere reduced both the filtered and unfiltered secondary pressure pulses by more than a factor of 50 (34 db). How much more the amplitude ratios were reduced could not be determined because the pressure amplitude with screen in place was in the background acoustic noise level of the

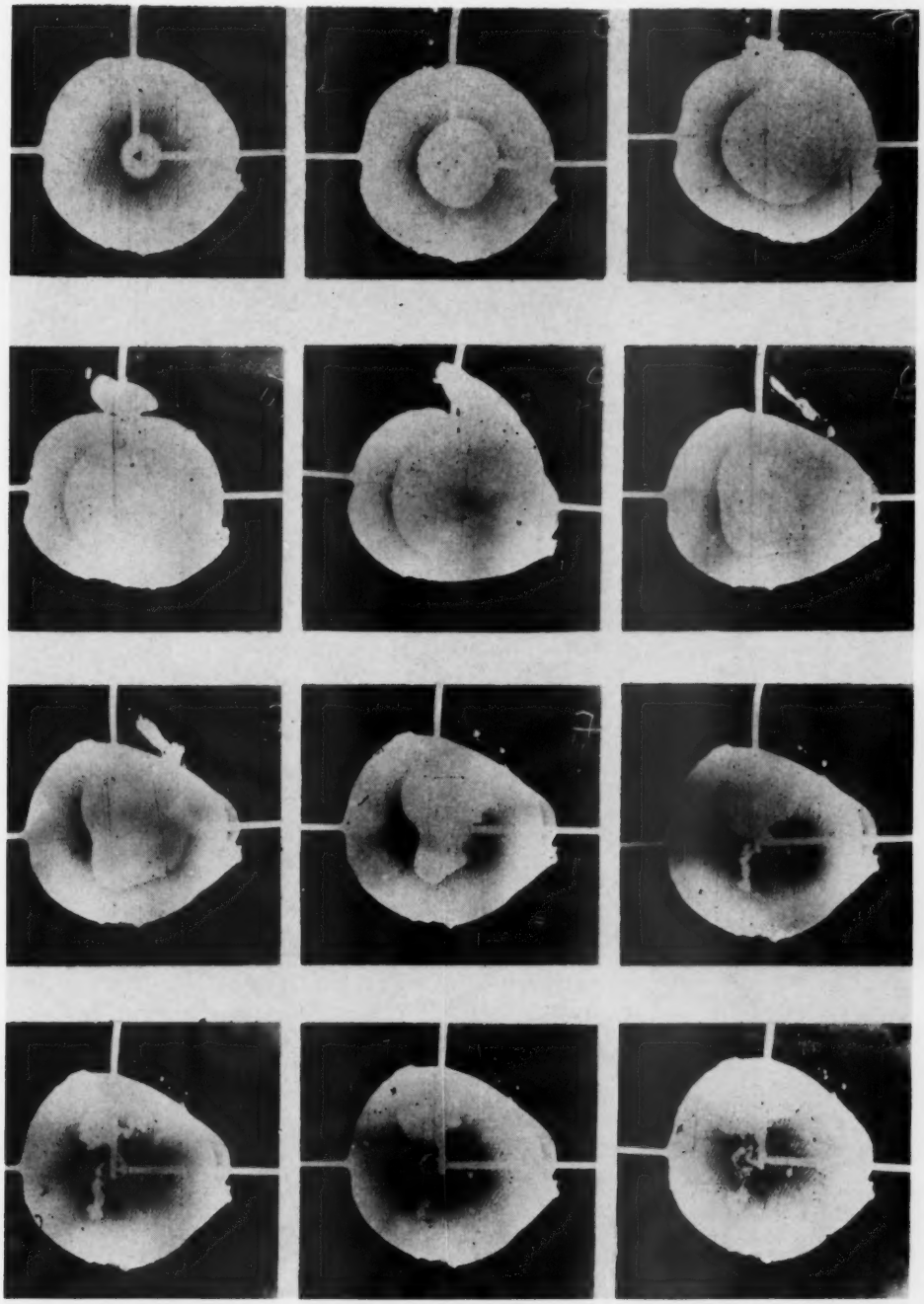

FIG. 1. Model equivalent of a 23-pound charge in 16-ft diameter perforated sphere 75 ft deep.

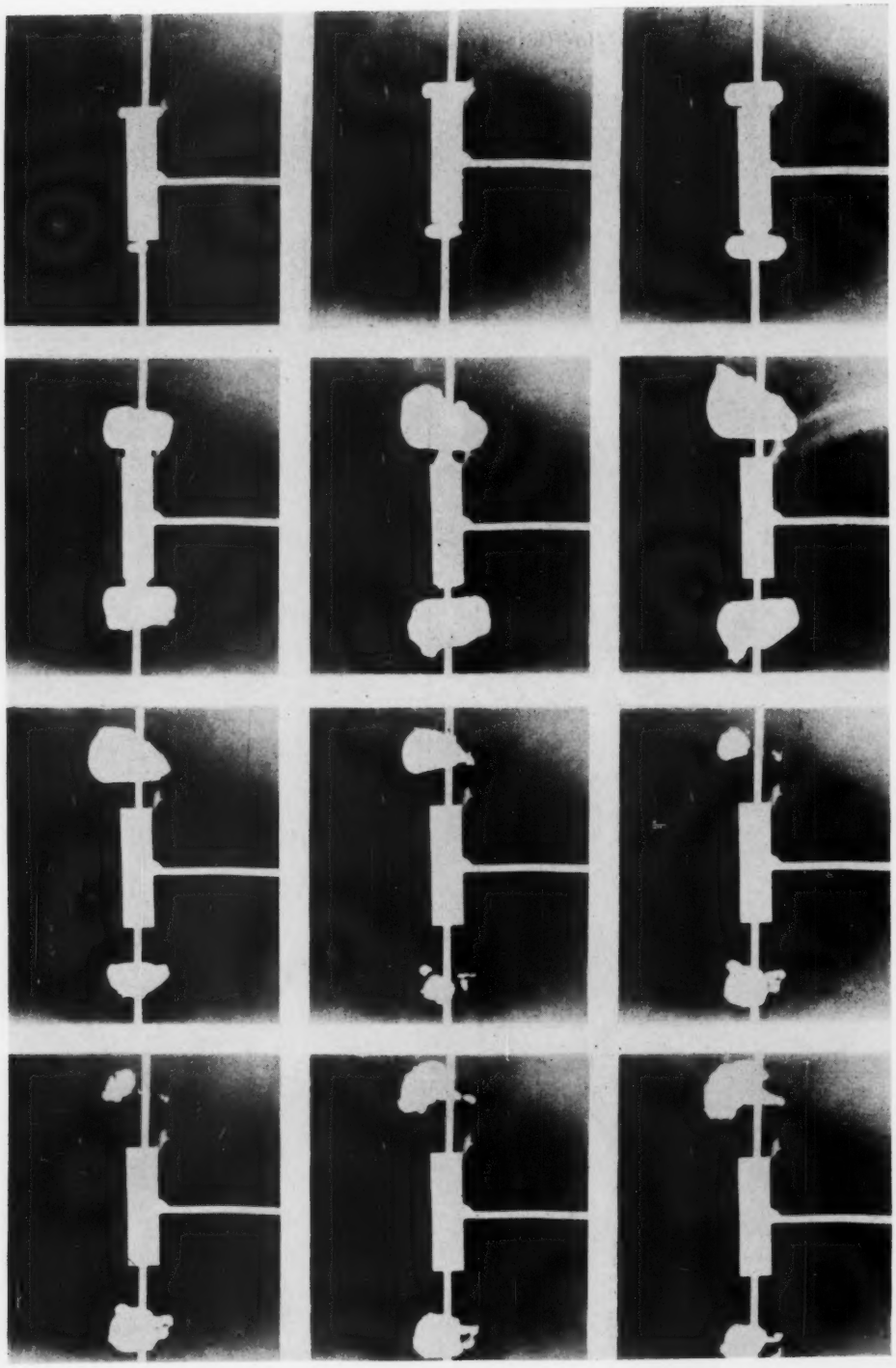

FIG. 2. Model equivalent of a 15-pound charge 75 ft deep in 3-ft diameter pipe 12 ft long.

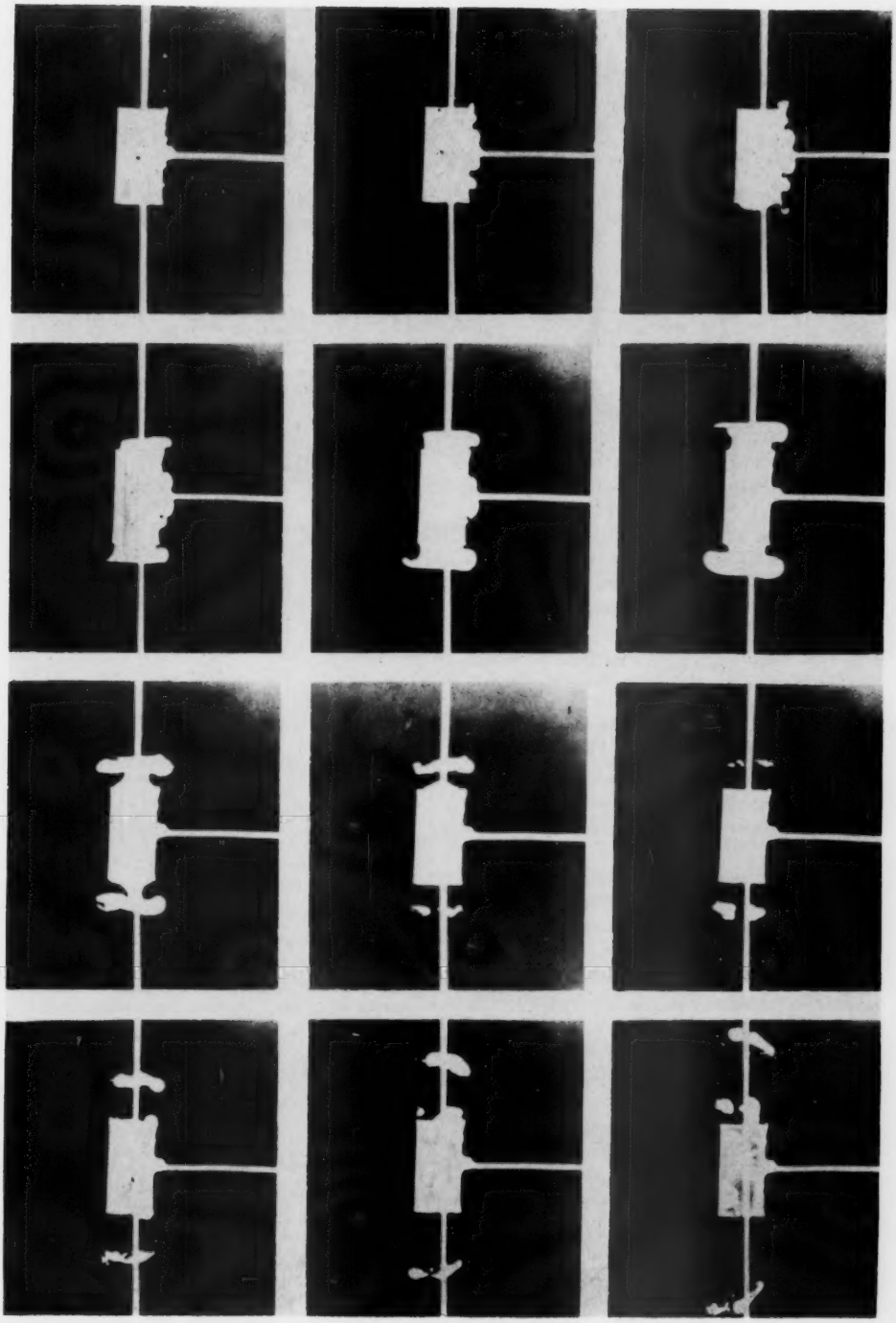

FIG. 3. Model equivalent of a 15-pound charge 75 ft deep in 5-ft diameter perforated pipe 10 ft long.

Table I

Method	Amplitude Ratio* Filtered	Amplitude Ratio* Unfiltered
Perforated Sphere (100-Mesh)	0.11	<0.02
Perforated Sphere (200-Mesh)	<0.02	<0.02
Pipe	0.25	0.1
Perforated Pipe	0.17	0.065

* Ratio of secondary pressure pulse amplitude with device in place to that with device removed.

model tank. The pipe was the least effective of the three devices.

The results shown in Table I for the solid pipe and the perforated pipe may not be the optimum results for these devices. No attempt was made to determine that the device parameters were optimum.

These devices are not expected to reduce significantly the seismic disturbance produced by the initial shock wave. The transmission loss of an acoustic plane wave in water with a frequency of 50 cps passing through a perforated steel plate is small (less than one db) for anticipated device parameters (Bolt, 1947).

NUMERICAL SOLUTION OF BUBBLE MOTION WITH BUBBLE ENCLOSED IN PERFORATED SPHERE

The results of the model experiments, as well as physical reasoning, suggest that the most positive device for damping the bubble motion is the perforated sphere. The effect of the perforated sphere is also amenable to numerical analysis.

To make the analyses tractable, the motion of the water is assumed entirely radial. This implies that there is no "buoyant" force acting on the bubble and, hence, no vertical migration of the bubble. This assumption is made in the simpler theories of bubble motion and yields an adequate description of the bubble radius with time over most of the bubble motion (Cole, 1948, p. 272). During most of the bubble motion the pressure variation in the water is small, and variations in water density may be neglected. That is, the water may be considered incompressible.

The Navier-Stokes equation and the equation of continuity become, in spherical coordinates with r the only space variable and the fluid incompressible,

$$\rho \frac{\partial u}{\partial t} + \rho \frac{\partial}{\partial r}\left(\frac{u^2}{2}\right) + \frac{\partial p}{\partial r} = 0 \qquad (1)$$

and

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 u) = 0. \qquad (2)$$

(The terms of the Navier-Stokes equation containing the viscosity are identically zero under the assumption of radial flow and incompressibility.) Integration of equation 2 yields

$$u(r, t) = \frac{f(t)}{r^2}. \qquad (3)$$

If a is defined as the radius of the gas bubble, we have

$$\dot{a} = u(a, t) = \frac{f(t)}{a^2}.$$

Substituting into (3), we obtain

$$u(r, t) = \frac{a^2}{r^2}\dot{a}. \qquad (4)$$

Inserting equation 4 into 1, we obtain

$$\frac{1}{r^2}\frac{d}{dt}(a^2\dot{a}) + \frac{1}{2}\frac{\partial}{\partial r}(u^2) + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0. \qquad (5)$$

We now assume that a perforated sphere surrounds the bubble at the radius R, and that there is a pressure discontinuity across the sphere of amount, $P_1 - P_2$ (see Figure 4). For fluid flowing at reasonable rates through a perforated sphere, the flow is turbulent downstream for a distance of about ten perforation diameters (Baines and Peterson, 1951, p. 473). We assume that the flow is smooth and radial right up to the screen on either side and that the entire pressure drop oc-

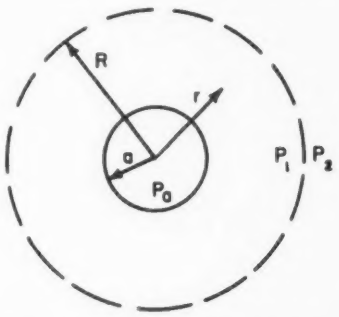

FIG. 4. Gas bubble in perforated sphere.

curs at the radius, R. Integrating (5) on r from a to infinity yields

$$\frac{d}{dt}(a^2\dot{a})\int_a^\infty \frac{dr}{r^2} + \frac{1}{2}\int_a^\infty d(u^2) + \frac{1}{\rho}\int_a^{R_-} dp + \frac{1}{\rho}\int_{R_+}^\infty dp = 0$$

or, simplifying,

$$\frac{1}{a}\frac{d}{dt}(a^2\dot{a}) - \frac{1}{2}(\dot{a})^2 + \frac{1}{\rho}(P_0 - P_a) + \frac{1}{\rho}(P_1 - P_2) = 0. \quad (6)$$

P_0 is the hydrostatic pressure and P_a, the gas pressure.

For Reynolds numbers applicable to the flow of water through the sphere during the significant part of the bubble motion, the pressure drop across the sphere may be written as

$$P_1 - P_2 = \tfrac{1}{2}\gamma\rho u(R, t)\,|\,u(R, t)\,|$$

and, finally, as

$$P_1 - P_2 = \frac{1}{2}\gamma\rho\frac{a^4}{R^4}\dot{a}\,|\,\dot{a}\,| \quad (7)$$

where γ is a parameter independent of u but dependent on the ratio of solid area to total area of the sphere and on the smoothness of the perforations (Baines and Peterson, 1951). The absolute hydrostatic pressure P_0 may be written as

$$P_0 = \rho g z \quad (8)$$

where z is a depth parameter. The gas pressure, P_a, depends on the charge weight and bubble radius according to the equation

$$P_a = kW^{1.25}a^{-3.75} \quad (9)$$

(Cole, 1948, p. 274).

Inserting (7), (8), and (9) into (6) and simplifying yields

$$a\ddot{a} + \frac{3}{2}(\dot{a})^2 + \frac{\gamma}{2}\frac{a^4}{R^4}\dot{a}\,|\,\dot{a}\,| + gz - \frac{kW^{1.25}}{\rho a^{3.75}} = 0. \quad (10)$$

For purposes of calculation (10) may be written as

$$a\ddot{a} + \frac{3}{2}(\dot{a})^2 + Ca^4\dot{a}\,|\,\dot{a}\,| + A - Ba^{-3.75} = 0. \quad (11)$$

The initial conditions must be chosen in such a way that near the beginning of the motion the total energy of the system is equivalent to that observed in actual explosion bubbles. In the numerical calculations reported hereafter, the following initial conditions were assumed:

$$\left.\begin{aligned} \dot{a} &= 0 \quad (12a)\\ E(a) &= \int_a^\infty P_a dV \quad (12b)\\ &= \frac{16\pi kW^{1.25}}{3a^{3/4}} = FWQ \end{aligned}\right\} t = 0$$

where $E(a)$ is the internal energy of the gas, F is the fraction of the total explosive energy going into the bubble oscillation system, and Q is the energy per pound of explosive.

The system of units used in the numerical analysis was the slug-ft-sec system. In this system, the coefficients and parameters used were:

$\rho = 2$ slugs/ft^3
$k = 1.55\times10^4$ lb$^{-1/4}$ ft$^{+1.75}$ (Cole, 1948, p. 274)
$g = 32$ ft/sec^2
$F = 0.4$ (Cole, 1948, p 277)
$Q = 1.49\times10^6$ ft lb/lb

Equation (11) was integrated numerically for several values of the parameters A, B, and C. The results of the integration are illustrated in Figures 5, 6, and 7.

Figure 5 shows how the bubble radius, a, varied with time for a charge of 15 pounds exploded at a depth of 100 ft ($z = 133$ ft). The value of C ($=\gamma/2R^4$) used for each curve is indicated on the figure. For C equal to zero, which implies no sphere, the energy of oscillation returns to internal energy of the gases at the end of the first oscillation, as it should. As C is increased, more of the oscillation energy is dissipated by the screen. This is evidenced both by the smaller maximum radius and larger minimum radius at the end of the first oscillation.

Figure 6 illustrates how the radius varies with charge size and depth for a value of C equal to 16×10^{-3}.

Figure 7 is a plot of the pressure difference,

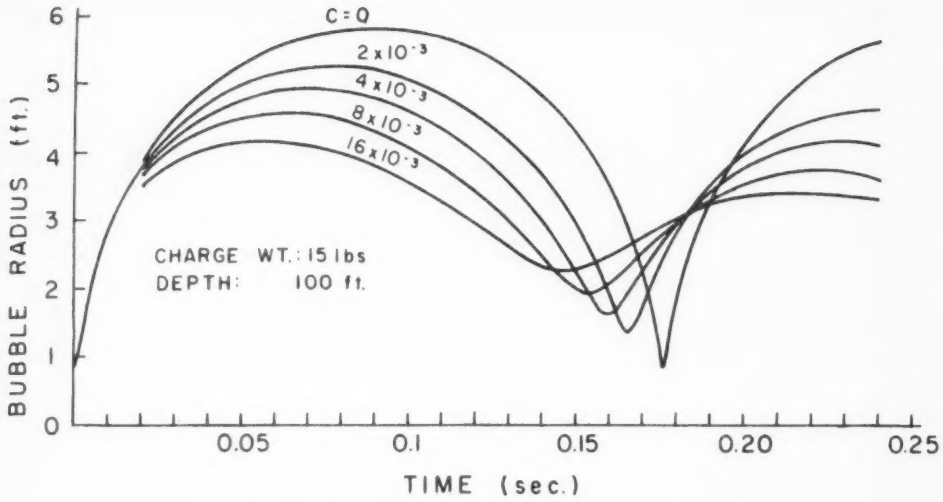

FIG. 5. Behavior of the gas bubble radius with time for several values of the perforated sphere parameter, C.

$|P_1-P_2|$, across the sphere as a function of time for several of the cases. These data are primarily of interest in engineering a sphere since it must have sufficient strength to withstand the pressure difference. The behavior of $|P_1-P_2|$ is determined once C is assigned (see equation 7).

Figure 8 shows the recorded behavior of model bubbles generated in small screens. The coordinates are the prototype coordinates. The motion of the fluid was actually not radial. This is evident on the recordings of the motion (Figure 1). Near the time of collapse of the bubble, the shape was very irregular—two bubbles being formed in one of the cases. The plotted radius in Figure 8 is the radius of a sphere that would enclose the same volume as the total volume of gas estimated from the observed bubble profiles. The values are approximate at best. The most significant behavior indicated is the increase in minimum radius and the decrease in period with increase of damping. This behavior is consistent with that shown in Figure 5. The radius of the more strongly damped

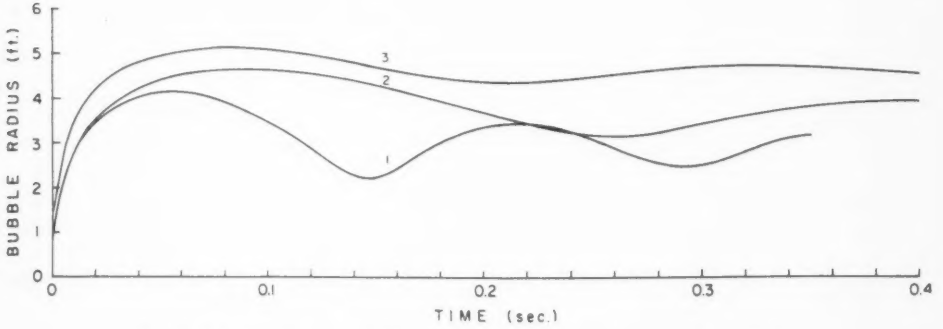

FIG. 6. Behavior of the gas bubble radius with time for constant perforated sphere parameter, C, but varying charge size and depth.

Curve	*Charge Wt.*	*Depth*	C
1	15 lbs	100 ft	16×10^{-3}
2	15 lbs	25 ft	16×10^{-3}
3	60 lbs	100 ft	16×10^{-3}

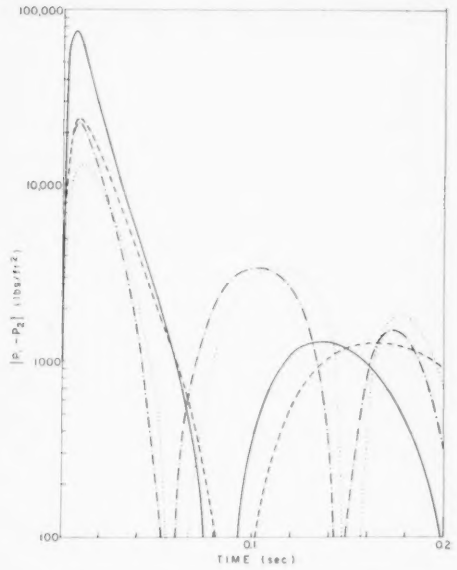

FIG. 7. Absolute pressure drop across perforated sphere with time for previous cases.

bubble was apparently larger than that of the weakly damped bubble. This apparent discrepancy may reasonably be explained as experimental inability to measure the third dimension of the bubble and estimation of the other two dimensions during the maximum expansion of the bubble.

Curve	*Symbol*	*Charge Wt.*	*Depth*	*C*
1	———	60 lbs	100 ft	16×10^{-3}
2	– – – –	15 lbs	25 ft	16×10^{-3}
3	—·—·	15 lbs	100 ft	16×10^{-3}
4	·····	15 lbs	100 ft	8×10^{-3}

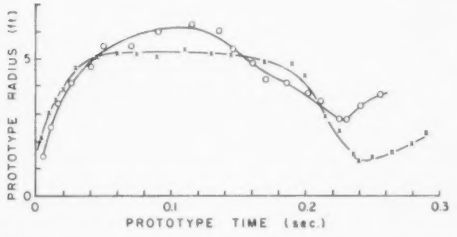

FIG. 8. Behavior of model gas bubble radius with time.

Curve	*Prototype Charge Wt.*	*Model Screen Size*
x	23 lbs	100 mesh
0	23 lbs	200 mesh

Table II

Charge Wt.	Depth	C	$\bar{a}$	$\bar{a}'$	R_1	R_2
15	100	2×10^{-3}	0.815	1.32	0.27	0.40
15	100	4×10^{-3}	0.815	1.61	0.15	0.27
15	100	8×10^{-3}	0.815	1.93	0.09	0.20
15	100	16×10^{-3}	0.815	2.25	0.06	0.15
15	25	16×10^{-3}	0.815	3.13	0.02	0.08
60	100	16×10^{-3}	1.29	4.38	0.03	0.10

Measures of the expected effectiveness of perforated spheres in reducing the seismic disturbance of the secondary pressure pulses are given in Table II. R_1 is the ratio of the peak pressures of the secondary pressure pulse with and without the sphere surrounding the charge. R_2 is the ratio of the energy radiated by the secondary pressure pulses with and without the sphere surrounding the charge. These ratios are computed using approximate theories described by Cole (1948, pp. 362, 374) and are given by the equations

$$R_1 = \left(\frac{\bar{a}}{\bar{a}'}\right)^{2.75}$$

and

$$R_2 = \left(\frac{\bar{a}}{\bar{a}'}\right)^{1.9}$$

where $\bar{a}'$ and $\bar{a}$ are the minimum bubble radii with and without the sphere, respectively.

PERFORATED SPHERE DESIGN CRITERIA

The following considerations apply to a single sphere surrounding the charge and of sufficient radius, R, that the bubble does not pass through the sphere. It would be clearly possible to obtain a total coefficient, C, by surrounding the charge by more than one sphere.

The effective, meridional, membrane stress, s, which the sphere must repeatedly withstand is

$$2\pi Rbs \geq \int\int \bar{k}\cdot(P_1 - P_2)_{\max}\overline{d\sigma}$$

or

$$s \geq \frac{(P_1 - P_2)_{\max}R}{2b}$$

where b is the thickness of the sphere (Figure 9). The actual local stress around the holes will exceed this value.

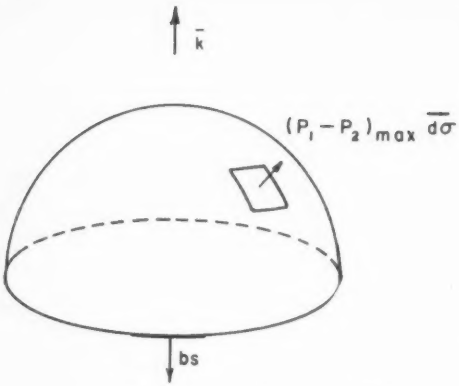

FIG. 9. Determination of the meridional membrane stress of a sphere.

The ratio, S, of solid portion of area to total area of the sphere may be determined by using design data of Baines and Peterson (1951, p. 471), once the value of γ is decided upon. From equations (10) and (11) we have

$$\gamma = 2R^4C.$$

For a sphere having a radius of 5 ft and a value of C equal to 16×10^{-3}, we have

$$\gamma = 20.$$

The value of S corresponding to γ equal to twenty is 0.72 for a sphere having perforations with radius large compared with the thickness.

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APPENDIX

Approximate theory reported by Cole (1948, p. 363) predicts that the maximum amplitude of the secondary pressure at a distance r is

$$P_{max} - P_0 = \frac{\bar{a}}{r} P_{\bar{a}}.$$

Using equations (9) and (12b) this equation becomes for a fixed charge size

$$P_{max} - P_0 = \text{Const } (E(a))^{11/3}.$$

The ratio of the energy radiated as a secondary pressure pulse, ΔY, to the initial oscillation energy, Y, is

$$\Delta Y / Y = \text{Const } (P\bar{a})^{1/2}$$

(Cole, 1948, p. 377). Expressing $P_{\bar{a}}$ in terms of $E(\bar{a})$ with the use of equations (9) and (12b), we obtain

$$\Delta Y / Y = \text{Const } (E(\bar{a}))^{5/2}.$$

GEOPHYSICS, VOL. XXVI, NO. 4 (AUGUST, 1961), PP. 437-446, 9 FIGS.

SOME TECHNICAL ASPECTS OF REFRACTION SEISMIC PROSPECTING IN THE SAHARA*

C. LAYAT,† A. C. CLEMENT,† G. POMMIER,‡ A. BUFFET‡

Abstract: The refraction method of seismic exploration was initiated in 1952 in the Northern Sahara after several difficulties were encountered with the reflection method. The first tests showed the existence of a deeper marker bed having a velocity of about 6,000 m/sec (20,000 ft/sec) which later proved to be the eroded surface of the basement. Now refraction can be employed, at least in certain regions, in detailed surveys although many difficulties in interpretation still exist.

Both field practices and methods of interpretation are discussed.

INTRODUCTION

The first seismic surveys in the Northern Sahara were made in 1951. Reflection methods were used initially, but several difficulties were encountered—surface conditions were unfavorable as a result of either a low velocity weathered zone or, on the contrary, a limestone caprock having a high velocity; at the base of the Mesozoic there was a formation having a high reflection coefficient that masked the Paleozoic horizons; numerous multiple reflections occurred that masked the less energetic, deeper, true reflections.

Although the exhaustive use of multiple detectors and pattern shots produced partial solutions to some of the difficulties, in many areas of Northern Sahara it has remained impossible to follow, with certainty, deep pre-Mesozoic horizons by reflection methods. Therefore, it was decided to use refraction methods.

The first tests, made as early as 1952, showed the existence of a deep marker horizon having a velocity of about 6,000 m/sec (20,000 ft/sec). This marker bed, which has been tied to the eroded surface of the crystalline basement, has proved to be remarkably consistent over the wide areas where it could be studied continuously on numerous profiles.

In certain zones this marker appears immediately behind the arrivals from the Mesozoic formations. Elsewhere, on the contrary, it is topped by occasionally numerous Paleozoic markers having velocities ranging from 5,000 to 5,800 m/sec (16,500 to 19,000 ft/sec). The study of these areas with multiple marker horizons is often very critical, but it furnishes valuable indications about the extent of the great sedimentary basins and about the shape of the different horizons.

We shall not discuss the geological interpretation of refraction surveys nor the role of these in the discovery of the great Saharan oil fields. We intend to describe the progress accomplished since the time of the first measurements with respect to interpretation and implementation, paying particular attention to certain technical aspects on which special consideration has been focused during these last years. We do not claim to offer a totally novel method. Moreover, we shall not be reluctant to refer to earlier publications about this subject and to mention their conclusions, if necessary.

EVOLUTION OF THE FIELD OPERATING TECHNIQUES

The evolution of the field operating techniques has been governed by the ever present concern of improving the output of the parties. To that effect, many different factors likely to slow down the operations in the field had to be considered. Of these factors, the following will be discussed:

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† Compagnie Generale de Geophysique, Algeria.

‡ Compagnie Francaise des Petroles, Algeria.

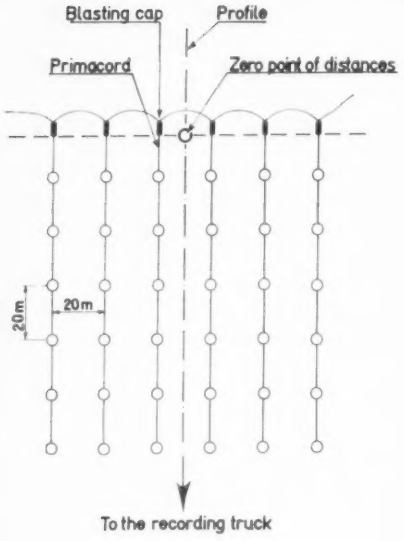

FIG. 1

natural noise, radio transmission, additional recording at different offset distances.

Natural noise

Atmospheric conditions, particularly wind, have a considerable influence on a party's output because operations can become practically impossible above a certain noise level. In an effort to combat this problem, the signal-to-noise ratio must be improved as much as possible.

The first thing to do is to try to increase the intensity of the emitted signal. To that effect, action can be taken on the explosive charge but means are very limited. The true problem is getting the best energy output from a given explosive charge. In the case of buried charges, the means consist mainly of choosing the optimum shooting depth, making proper use of "potting," and tamping the shot holes adequately.

With respect to surface shooting, a technique had to be adopted while working in certain erg (loose sand) areas. An important group of experiments has made it possible to study the influences of the different parameters. These experiments are the subject of a detailed article (Buffet and Layat, 1960), from which we shall use the accepted design for the shot pattern. This layout shows a rather large spacing of the charges (20 meters) and relatively heavy individual charges (25 kilograms). For instance, the pattern adopted for a total charge of 900 kg would be 36 charges of 25 kg laid out on 6 lines of 6 charges parallel to the profile, each one primed with primacord, 20 meters between the charges and 20 meters between the lines (Figure 1). In order to modify the total charge, the number of lines is increased or decreased. Thus, the charge in one line constitutes the practical individual charge.

Without operating directly on the intensity of the emitted signal, the signal-to-noise ratio can also be improved by making variations at the recording end on the parameter affecting the seismic trace, e.g., number of geophones, distance between geophones, and geophone plants. Extensive but unrelated experiments have been made and grouped. This activity has led to these generalities. Regarding the number of geophones, for a distance of 10 meters between geophones, the dephasing of the noises is secured in Saharan terrain conditions and the statistical law of $\sqrt{n}$ applies quite well if the different geophones of one trace are carefully laid out in an area which has a very small dimension (in comparison to the wave lengths) in the direction of propagation of the waves and if the difference of elevation between the geophones is small. The effect of the distance between the geophones is represented qualitatively by the curve of Figure 2, where the abscissas are the distances d and where the ordinates represent the ratio

$$\frac{\text{ratio signal-to-noise for } d \text{ meters}}{\text{ratio signal-to-noise for 0 meters}}.$$

In approximate value this curve applies quantitatively to patterns comprising up to 24 geophones, at least within the limits of our experiments. However, individual measurements show

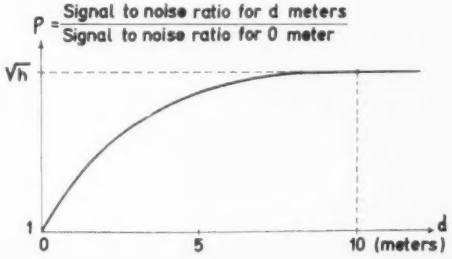

FIG. 2

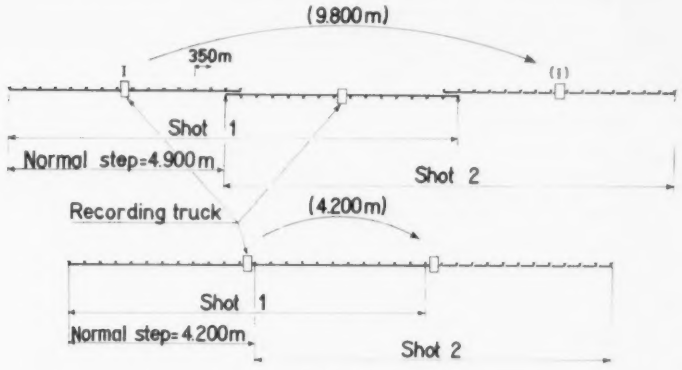

FIG. 3

a great dispersion and can depart considerably from this curve. On the other hand, it is conceivable that the minimum decoupling distance for the noise varies closely with the nature of the ground. Thus, it can be established that in sandy regions without vegetation, noise is almost completely decoupled at distances of about one meter. However, if there is much vegetation, a much wider spacing is necessary because in that case noise is caused not only by the displacement of particles in the vicinity of each geophone, but also by the perturbation caused by the movement of the vegetation.

The preceding results are valid only if the planting of the individual geophones is similar. In effect, the planting can be considered satisfactory if each geophone is covered with about 4 inches of soil. This presents no problem at all in sandy regions or at least wherever the ground surface is soft. It is quite different in areas of hard outcrops and the experiments made under such conditions show that, in cases where it is not possible to ensure a correct planting of many geophones, it is better to use a restricted number of properly buried geophones than a large number, poorly planted. Yet, the results to be expected from multiple detection are such that, in hard ground, the use of additional personnel or even of specially designed equipment seems justified (particularly since the low-frequency, small-sized, and low-priced geophones have appeared on the market).

Radio transmission

For a long time, the radio transmitting conditions had an important influence on the performance of the parties because outside of certain hours it was impossible to establish contact between observer and shooter with the available power and frequencies.

A significant improvement was made when the VHF equipment was put into service and nearly perfect communications could be established at any hour of the day. The topographic variations usually had only a weak screening effect on the transmissions, except in some particularly unfavorable cases where the topography was simultaneously rugged, nearby, and compact (e.g., limestone cliffs).

Additional recording at different offset distances

Certain regions where there are several marker beds having approximately equal velocities are often quite difficult to survey, and it is very often inadequate to have only one record per seismometer spread shot from a single distance in both directions. Additional recordings involve extra "layouts" and slow production considerably. Sometimes certain shots must be sacrificed, even though they would be very useful for the interpretation.

Consequently, it has been found convenient to record regularly two shots in each direction at different offset distances. In order that the number of actual shots not be increased (and thereby no increase in the use of explosives), it was necessary to double the length of the seismometer spread, only half of it being moved between shots. This was done at first by using two complete cable assemblies unreeled end to end with two recording trucks and, at a later time, by introducing reversible cables using a single recording truck.

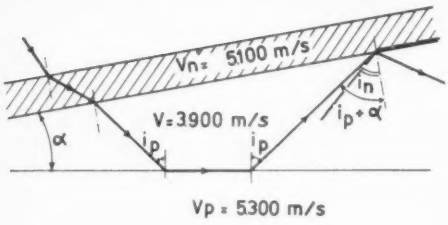

FIG. 4

The cables are moved as in reflection seismic surveying, using the split-spread method.

Figure 3 shows the spreads actually used in both cases. The customary spacing (the effective advancement at each move) can be seen. A distance of 350 meters between traces is generally used for investigation of the basement marker.

Assuming that there are but few complementary shots, an average monthly production of about 160 km (100 miles) can be achieved with this kind of equipment.

When sedimentary marker beds are surveyed, it may be necessary to reduce the distance between traces (200 meters for instance) and sometimes reduce considerably the interval between shotpoints, particularly if some of the surveyed markers can be followed for short distances only. The mode of operation of the recording truck remains unchanged, several shots then being systematically recorded for a single position of the recording truck.

EVOLUTION OF THE INTERPRETATION TECHNIQUES

Examination of the records

The accumulation of a large number of records has enabled significant progress to be made in the analysis of records. One of the principal sources of difficulties encountered in this examination is the frequent presence of marker beds having similar velocities. Consequently, there are long interference zones and considerable variation of the critical distances on the time-distance curve in the case of angular unconformity between these markers. In certain regions, it is even occasionally impossible to follow these markers when the unconformities are too strong.

In an effort to give a concrete example concerning this last point, we will mention a region where two markers have been studied, one having a velocity of 5,100 and the other 5,300 m/sec (16,700 and 17,350 ft/sec). They are separated by formations having a velocity of 3,900 m/sec (12,800 ft/sec). Computation shows that it is not possible to follow the 5,300 m/sec marker if the unconformity is above two and one-half degrees. In this case it is evident that the waves are totally reflected at the base of the 5,100 m/sec marker, as shown by the graph in Figure 4.

Arguments of this kind, based exclusively on

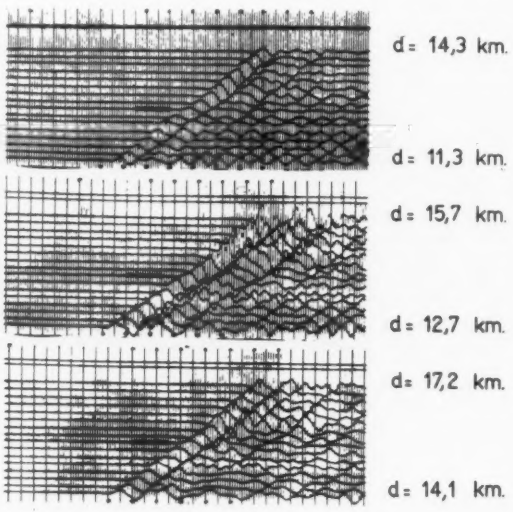

FIG. 5a

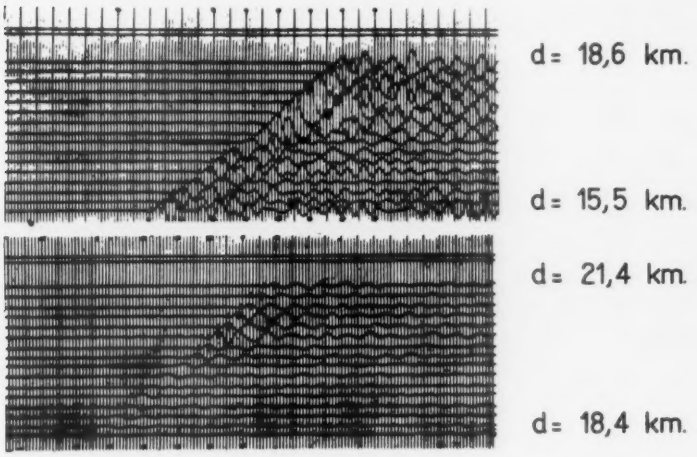

FIG. 5b

the laws of geometrical optics, apply properly only to marker beds of like nature (sedimentary) and of comparable thickness, i.e., transmitting the refracted energy in an approximately equivalent way. If one of the marker beds has a considerable thickness, as is the case for the basement, and if the overlying marker beds are relatively thin in comparison to the transmitted wave lengths, it is possible to record the arrivals corresponding to the deep marker even if the apparent or true velocities of the upper markers are greater than that of the deep marker.

Another critical point encountered in studying records concerns the crossing of fractured zones. Faults that are intersected along the profiles are seldom shown on records by outstanding events, such as a sudden shifting of the time-distance curve, considerable losses in energy, or conspicuous diffraction hyperbolas. In most cases, a break on the time-distance curve is shown only when it does not shift as the shotpoint is changed, or simply a modification in the form of the traces (amplitude, frequency) not dependent on the shot distance. These phenomena are often evident in one shooting direction only, and the throw is sometimes difficult to determine.

Figure 5 shows a classic example of the intersection of a fracture zone in the Sahara. The intersection is shown by a sharp change in appearance of the trace near the ninth trace for the same geophone spread shot from 5 different shotpoints. It is also apparent that traces 1 through 8 show greater amplitudes even though they are at a greater distance from the shotpoint.

Such phenomena can be studied in detail only if several records are available with different shot distances for each seismometer spread. This justifies using as a minimum the double control spread described previously.

Method of record interpretation

The interpretation method used initially has been largely inspired by the one developed at the Gulf Research & Development Co., by L. W. Gardner, which is based on the determination of the delay times related to the depths.

This method has been subjected to important modifications which are too involved to examine here in detail. We shall merely point out the two main considerations which have guided us; an elaborate as possible mechanization of the computing operations by developing the calculative data processing to the maximum (this is detrimental to graphical methods which are more subject to "human factors"); the development of a checking system permitting the step-by-step verification of the interpretation of a profile, thus avoiding as much as possible later modifications which, however small, often involve a complete re-evaluation of significant portions of the results.

Influence of anisotropic phenomena

The attempts to identify the marker beds and the determination of depths and offsets show that

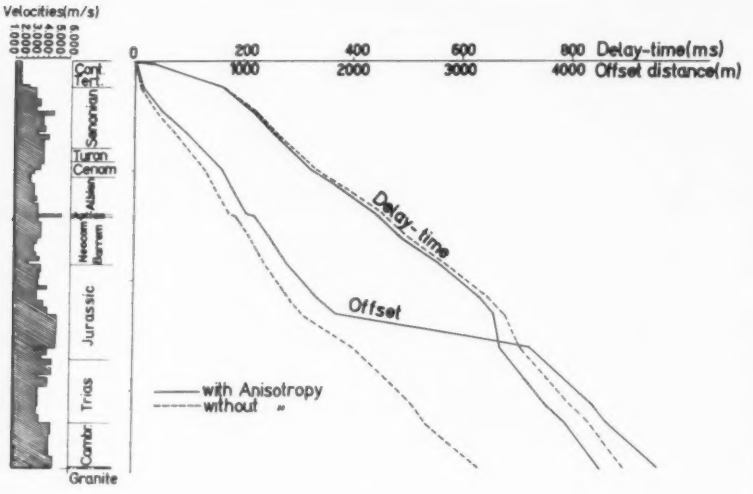

FIG. 6

it is essential to take anisotropic phenomena into account. A relatively large number of measurements have been made to that effect in the Sahara. Some have been the subject of previous articles (Cholet and Richard, 1954; Dunoyer De Segonzac and Laherrere, 1959) and it is not necessary to retrace these measurements. These are the essential results. The depths determined by means of velocities obtained from a well velocity survey, without taking anisotropy into account, often lead to the location of marker beds in the middle of homogeneous formations without velocity differentiations, or perhaps at the level of a low velocity formation surrounded by faster layers. Such anomalies are eliminated when anisotropy is brought into play as it has the effect, for the same delay time, of increasing the calculated depth. Thus, it has been possible to identify satisfactorily the different markers under investigation. The influence of anisotropy on the offset value is still more important, particularly when a high velocity formation, even a thin one, is affected by strong anisotropy. This phenomenon can be noticed in a great portion of Northern Sahara where the anhydrite of the Lias, which already has a high vertical velocity (5,000 m/sec or 16,400 ft/sec at Hassi Messaoud), also has a high coefficient of anisotropy $k = 1.16$. Figure 6 shows the results obtained from the survey of a well in the Hassi Messaoud field. It is evident that the error made on the offset by neglecting anisotropy exceeds 50 percent. If the determination of the offset distance had been made by taking into consideration a single stratum having a velocity equal to the average velocity to the depth of the marker horizon, the error would be even larger. The offset distance would be found to be half that actually required. The large offset values thus found (about 5 km at Hassi Messaoud for a 5,900 m/sec marker situated at a depth of 3,700 meters) are confirmed by other considerations. Thus, the correlation of a fault in both shooting directions as well as the study of the zones where seismic energy increases markedly in the proximity of the critical angle, gives rise frequently to values equal to twice the offset distance of 10 to 15 km for the basement marker. The result is that structural anomalies which are found in certain regions showing a shift clearly inferior to these offset values must necessarily be attributed to overburden formations. In fact, reflection seismic, as well as the study of the shallower refraction marker horizons, shows the existence of rather pronounced local unconformities which are related to quite distinct velocity discontinuities. It is important that the nonconformity surfaces be determined as much as possible so that their effect can be compensated when the deep marker horizons are studied.

USE OF MAGNETIC RECORDING IN REFRACTION

The advent of magnetic recording in refraction methods had a certain number of important consequences, a few of which are discussed.

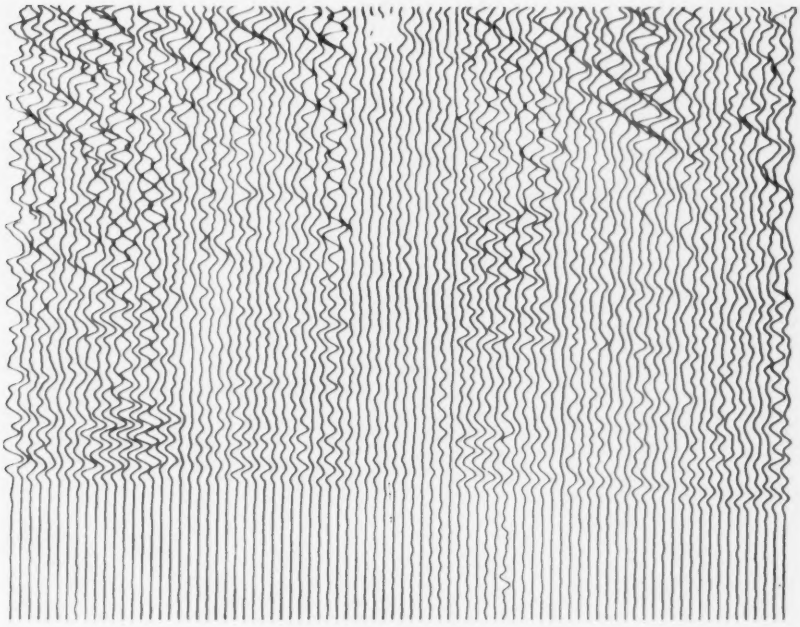

FIG. 7a

Decrease of explosive consumption—The decrease is caused mainly by a lowering of the safety margin required in standard recording. The lowering of the safety margin is in consideration of possible performance variations of the shotpoints. The effects of these variations can now be reduced by varying the gain at the playback.

Record interpretation and presentation—In the central processing office, each record corresponding to a particular marker bed undergoes elevation and W.Z. corrections as well as X/V corrections for each trace (X = distance from shotpoint to seismometer trace; V = velocity of the marker). Thus, "intercept time records" are obtained which can later be assembled into continuous sections by considering the traces common to adjoining records. An example of such a section is given in Figure 7 in three different modes of presentation as follows: normal galvanometer, variable area, and variable density. This process produces a record which is clearer and much more complete than a simple curve traced on cross-section paper.

Figure 8 represents a section of a profile displaying a rather noticeable fault in both shot directions.

Of course, each section thus obtained is strictly representative of the marker bed only if the velocity V chosen for the correction X/V is exactly that of the marker. In fact, it is advisable to study simultaneously the corresponding sections obtained from shots in opposite directions. The calculations and verifications applied to these sections are the same as those used in conventional exploitation.

Stacking—The adding of individual shots has been made possible through magnetic recording. As a rule, it is only a makeshift method which consumes a great deal of time and requires a lot of explosives. Admitting that the recorded signal amplitude is proportional to the charge, n shots of a charge q give the same amplitude as a single shot of a charge nq, but with a noise statistically multiplied by $\sqrt{n}$. It may be necessary to revert to this method when big charges cannot be shot, as is often the case in populated areas.

Compositing of traces—Determination of the typical signal related to a particular marker bed—Figure 9 shows the use of the compositing possibilities offered by magnetic processing.

Each of the 7 traces at the top of this figure represents the sum of 72 traces distributed over some 16 km of profile (10 miles). A strong analogy can be noticed in the shape of the first 5 traces, at

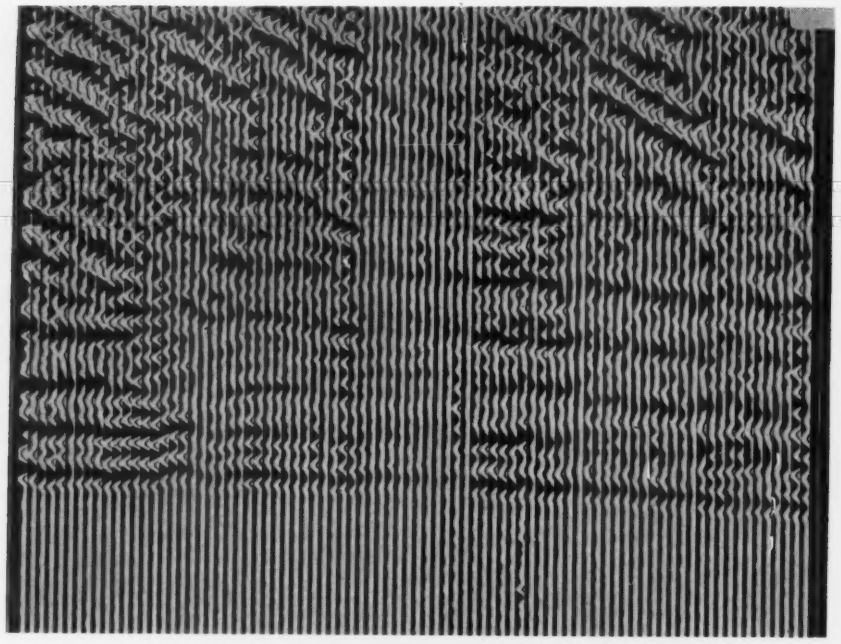

FIG. 7b

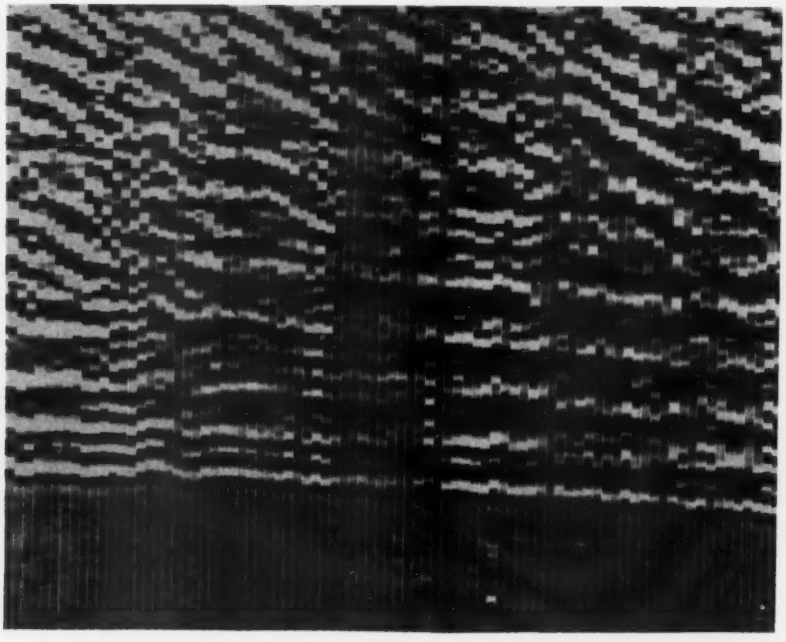

FIG. 7c

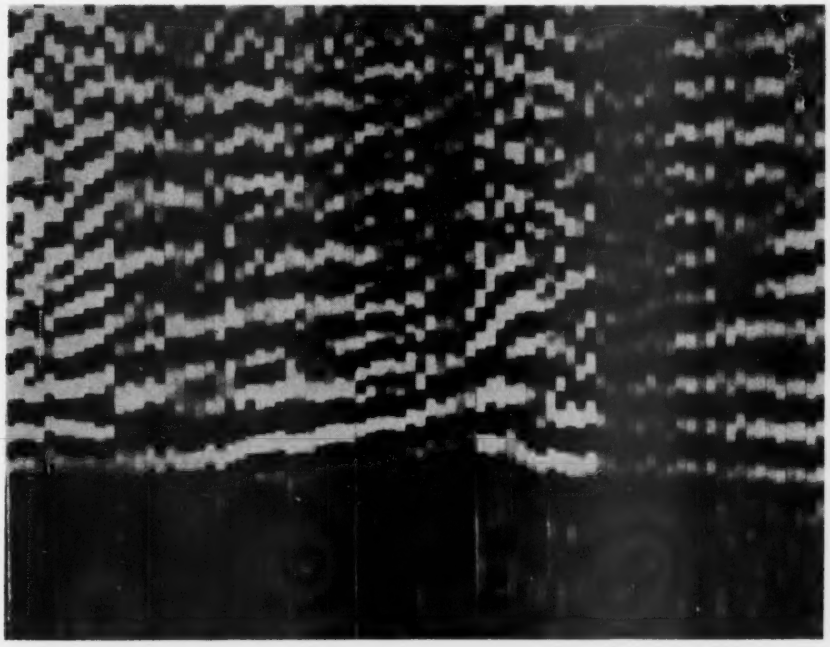

FIG. 8a

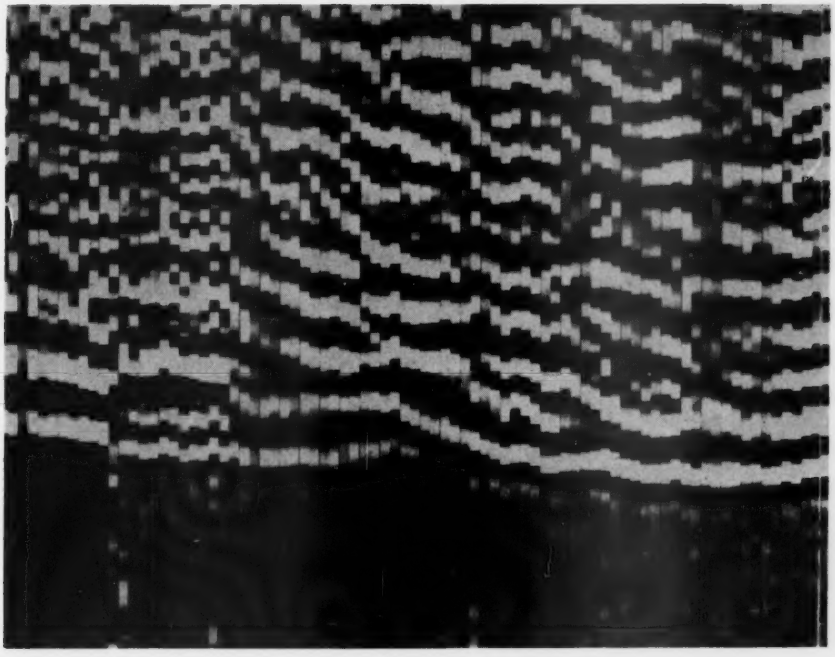

FIG. 8b

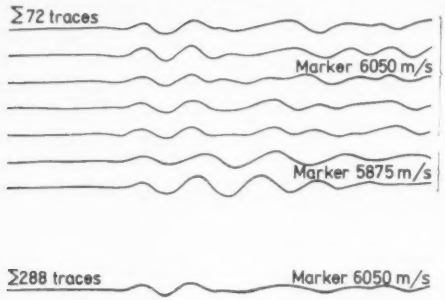

FIG. 9

least on the first 300 m/sec of the signal, whereas the appearance of the last two is rather different. This change of shape of the signal agrees with a change of nature of the marker that has been evident during the detailed study of the corresponding profile. The velocity of the marker bed changed from 6,050 to 5,875 m/sec (19,850 to 19, 250 ft/sec). It can be surmised that the shape of the signal seen on the first 5 traces is characteristic for the 6,050 m/sec marker.

A still more extensive compositing is capable of providing an even sharper outline of this characteristic signal. This has been done with the bottom trace of the figure which is the sum of the first 4 traces. A strong attenuation of every signal except the one studied can be noticed.

CONCLUSIONS

Following a marked decline at the end of the large-scale reconnaissance phase, refraction enjoys a renewed activity in the Sahara. This is certainly caused by the discovery of fields such as Hassi Messaoud in primary sands situated below the present investigating depth of reflection methods, but also caused by the efforts and continuous progress accomplished since refraction work started in these regions.

Refraction is now prepared, at least in certain regions, to carry out detailed surveys (which, for a long while had been withheld from it) successfully, under good as well as economical conditions, at cost prices per kilometer often competing with those of reflection.

These efforts must be continued unceasingly because many difficulties concerning the interpretation of the data still exist. It is also advisable to use every possible means in order to extract more information from the records through an intensified study of secondary arrivals. A large number of experiments have been made in this area and a method based on the correlation of the traces in proximity to the critical angle has been developed which gives excellent results in certain regions. This is an incentive to continue surveys which, although they may not always lead immediately to substantial results, will eventually give good returns.

ACKNOWLEDGMENTS

The author wishes to thank Compagnie Francaise des Petroles (Algerie) and Compagnie Generale de Geophysique for providing the means for a large number of experiments in the field which have made possible most of the progress accomplished in refraction seismic in the Sahara.

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GEOPHYSICS, VOL. XXVI, NO. 4 (AUGUST, 1961), PP. 447–451, 5 FIGS.

ON THE PRINCIPLES OF GEOCHEMICAL OIL PROSPECTING*

L. STEGENA†

Abstract: The geochemical prospecting method is based upon the circumstance that the gases of the oil reservoirs migrate vertically as demonstrated by sensitive analytical techniques.

Some unsatisfactory results and the criticism raised concerning the method have made necessary the investigation of the fundamental principles of the process.

Gas migration is caused partly by differences in concentration, partly by differences in pressure. The migration caused by the former factor is termed diffusion, that caused by the latter one is called effusion. This paper attempts the quantitative treatment of diffusion.

The results of this treatment are as follows: (1) In case the reservoir is situated at a great depth and in case the superincumbent layers are highly impermeable, a time interval is necessary to reach steady-state diffusion which is significantly above the lifetime of the reservoirs; (2) In other cases, where the depth is not too great, or the superincumbent layers are fairly permeable, a steady-state diffusion has to be reckoned with.

The chemical prospecting for oil found a widespread application after the work of Laubmeyer (1933) and Sokolov (1933). After the 'thirties it was utilized on a quite large scale in Europe as well as in America.

Lately, the process has been criticized by Kalinin (1955) and Jasenev (1954). The critics have questioned the vertical migration of hydrocarbon gases which is the base of the said process. These doubts as well as the changing success with which the process was employed make it necessary to clarify the fundamental principles.

A gas moves from one point of space to the other as a result of differences of pressure or of concentration. The displacement caused by differences in concentration is called diffusion, that caused by pressure differences is called effusion. Migration is brought about by the joint action of these two factors.

Diffusion is governed by Fick's law (1855), according to which

$$\frac{\partial C}{\partial t} = D \cdot \nabla C,$$

the temporal change of concentration at a given point being directly proportional to the Laplace operator of concentration. The proportionality factor is the coefficient of diffusion. This is the differential equation which has to be solved if we wish to know the concentration prevailing at a given depth z at a given instant t. To simplify the solution, we have to introduce a model of the oil reservoir which represents the natural circumstances in a good approximation and does not yield any too complicated edge conditions.

Let us assume that:

(1) The reservoir was formed instantaneously at the time $t=0$, and at the depth $z=h$.
(2) The concentration of gases in the reservoir does not change significantly by the diffusion of the gases.
(3) On the surface, $z=0$, the concentration of the gases passed there by diffusion is negligibly small.
(4) The reservoir is covered by a sedimentary series of the average diffusion coefficient D.
(5) The lateral extension of the reservoir is significantly greater than its depth. In that case, the one-dimension equation

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2}$$

applies.

These assumptions approximate the natural conditions quite well and yield the following mar-

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† Roland Eötvös Geophysical Institute, Budapest, Hungary.

ginal conditions for the mentioned differential equation:

$$C_{(0,z)} = 0, \tag{1}$$

$$C_{(t,h)} = C_0, \tag{2}$$

$$C_{(t,0)} = 0. \tag{3}$$

The original differential equation and conditions (2) and (3) are satisfied by the very simple function

$$C'_{(t,z)} = C_0 \frac{z}{h}$$

which, however, does not satisfy condition (1). Therefore, we will regard the concentration existing at the time t in the depth z as consisting of two parts:

$$C_{(t,z)} = C'_{(t,z)} + C''_{(t,z)}.$$

The conditions concerning the function $C''_{(t,z)}$ are evidently

$$C''_{(0,z)} = -C_0 \frac{z}{h}, \tag{4}$$

$$C''_{(t,h)} = 0, \tag{5}$$

$$C''_{(t,0)} = 0. \tag{6}$$

The well-known particular solution is

$$C''_{(t,z)} = A_n e^{-a^2 D t} \sin az$$

which satisfies condition (6), but which will not satisfy condition (5) unless

$$a = \frac{n\pi}{h}$$

where n is an integer. To satisfy condition (4), the constants A_n have to be chosen so that

$$\sum_{n=1}^{\infty} A_n \sin \frac{n\pi}{h} z = -C_0 \frac{z}{h}.$$

The left side of the equation is the Fourier series of an odd function. Therefore, the coefficients are yielded by the well-known Fourier integral:

$$A_n = \frac{2}{h} \int_0^h f(x) \sin \frac{n\pi x}{h}\, dx$$

$$= \frac{2}{h} \int_0^h -C_0 \frac{z}{h} \sin \frac{n\pi z}{h}\, dz$$

$$= \frac{2C_0(-1)^n}{\pi n}.$$

Carrying out the substitutions, we have

$$C_{(t,z)} = C_0 \left(\frac{z}{h} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} e^{-(n^2\pi^2/h^2)Dt} \sin \frac{n\pi z}{h} \right).$$

This equation yields the concentration prevailing at a depth z at an instant t, when the gas concentration in the depth of the oil reservoir is C_0, the depth of the reservoir is h, and the average diffusion coefficient of the superincumbent layers is D. Concerning these constants, the following assumptions may be made.

The concentration C_0 is the concentration of the dissolved gases in the immediate vicinity of the reservoir. The dissolved gas is mainly CH_4, the solubility of which has to be considered at 50°C and 100 atmospheres pressure, which may be considered as average values for the oil reservoirs. Seidell (1941) gives the dependence on temperature of the solubility of methane in water at one atmosphere pressure and its dependence on pressure at 25°C. Assuming the pressure function to have the same shape at 50°C as at 25°C, we obtain $C_0 = 0.1$, volume-to-volume concentration of CH_4.

The diffusion coefficients of rocks may be taken from P. L. Antonov (1954). The diffusion coefficient of the impermeable clay layers is 10^{-8}–10^{-7} cm² sec^{-1}. The diffusion coefficient of the rest of the layers is higher than that. Another author, Geller (1959), assumes a diffusivity of 10^{-9}–10^{-8} cm² sec^{-1}. If the impermeable cover is not pure clay, being interbedded with more permeable sandy horizons, the average diffusion coefficient may, in the sense of Fick's equations, be calculated by the formula

$$\frac{1}{D} = \frac{a}{D_s} + \frac{b}{D_c}$$

where D_s is the diffusivity of sand, D_c that of clay, a the total thickness of sand, b that of clay in the profile if the total thickness is $a+b=1$.

It follows from this formula that the average coefficient of diffusion is between 10^{-7} and 10^{-8} if the cover contains more than 10 percent clay and if the coefficient of diffusion of clay is 10^{-5}. Thus, in an extreme case the average coefficient of diffusion of the cover is 10^{-8}; however, in the general case it will amount to something like 10^{-7} and it may assume values of 10^{-6} and 10^{-5}.

Finally, the average depth of the oil reservoir may be assumed at 10^5 cm. The curve C vs t obtained for a depth $h = 10^5$ cm is also valid for other h' values of depth, only the time scale has to be distorted so that

$$\frac{t}{h^2} = \frac{t'}{h'^2}$$

be fulfilled.

I have computed the variation of the concentration for different depths and times. According to curve t_3 of Figure 1 the time necessary to reach steady-state diffusion is 10,000 million years, if $D = 10^{-8}$ cgs and $h = 10^5$ cm. However, if $D = 10^{-6}$ cgs, or $h = 100$ m, this time decreases to 100×10^6 years, which is already a period commensurable with the lifetime of oil reservoirs.

Figure 2 shows the distribution of gas concentration in a depth of two meters, which may be taken as the average depth of gas sampling. The point at which the steady-state diffusion is arrived is indicated on the graph by an asterisk. According to this graph this is the time, or at the most twice to four times the time, which must elapse before the geochemical research has a good chance to indicate the presence of an oil reservoir with success. Figure 3 shows in tabulated form the times necessary to reach steady-state diffusion, in the function of the parameters D and h, in million years, as well as the steady-state concentrations prevailing at a depth of two meters. If the above reservoirs are situated too deep or covered with massive rocks, no significant diffusion of gases may be expected.

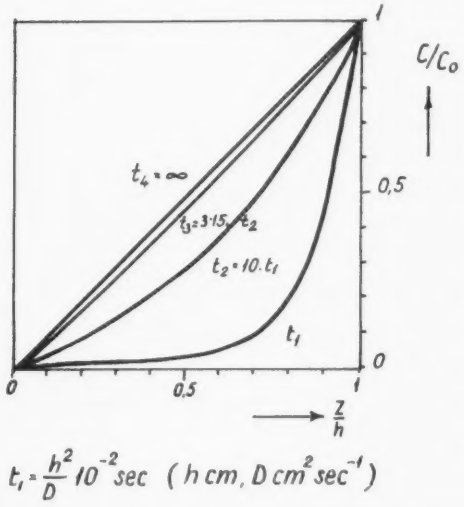

FIG. 1

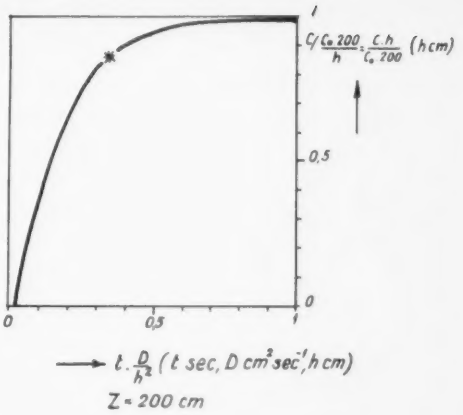

FIG. 2

Before attempting prospecting of a given oil reservoir by gas detection, it is worth-while to estimate, on the basis of the h and D values to be expected as well as on the presumable age of the oil, whether diffusion has reached the steady state in the case in question. By this means, a greater efficiency of geochemical prospecting for oil may be accomplished.

Thus, in one Hungarian oil area the depth of the reservoir was 800 to 1,200 meters, the impermeable layers in the sequences traversed by drilling amounted to about 10 percent, so that the average diffusivity could be set at 10^{-7}–10^{-6} cgs. Since the oil reservoir is of upper Pliocene age, no steady-state gas diffusion may be expected as yet.

The intensity Q of the diffusion may be computed from Fick's first law,

$$Q = D \frac{\partial C}{\partial z}$$

h (m) / D ($cm^2 sec^{-1}$)	3000	2000	1000	500	330	250
1.10^{-8}	90,000	40,000	10,000	2,500	1,100	620
1.10^{-7}	9,000	4,000	1,000	250	110	62
1.10^{-6}	900	400	100	25	11	6·2
1.10^{-5}	90	40	10	2·5	1·1	0·62
1.10^{-4}	9	4	1	0·25	0·11	0·062
C stac → cm^3/cm^3	07.10^{-4}	1.10^{-4}	2.10^{-4}	4.10^{-4}	6.10^{-4}	8.10^{-4}

FIG. 3

and from Figure 1. The total amount M of gas diffused up during the interval T is given by the integral

$$M = \int_{t=0}^{T} Q dt.$$

Thus, if $D = 10^{-6}$ cgs and $h = 10^5$ cm, during 310×10^6 years a total amount of 0.008 cubic meters of gas has escaped per unit surface. Therefore, it is evident that our starting assumption is valid.

Let us return to the basic differential equation. It is clear that in reality there is also some lateral diffusion. However, considering the average extension and depth of the oil reservoirs, this cannot be significant.

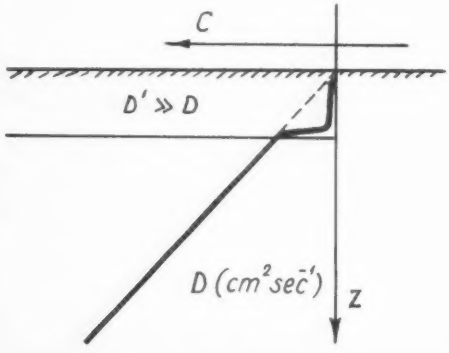

FIG. 4

The results are more significantly influenced by the circumstance that the gases are dissolved and absorbed in their upward migration by solid and liquid rocks. As a consequence, the process of diffusion is slowed down. These factors were taken into consideration by Antonov in the course of his measurements.

The above considerations shed a light upon the conclusion of J. Juranek (1958) which stated that it is the gaseous hydrocarbon content of the near-surface layers which takes an important part in causing gas anomalies, even when the gas concentration of these layers is far below that of the deeper-lying ones. The reason for this is that the time to reach steady-state diffusion varies with the square of depth, so that these will be the first to yield a steady-state diffusion. According to this view, the geochemical method is a structure-prospecting, rather than a direct oil-prospecting, method.

The frequent occurrence of ring anomalies or halo effects may also be explained in this way. In these cases the anomaly is not brought about by the oil deposit situated deep, but by some layer closer to the surface. Of the layers folded into an anticline, some, generally the ones closest to the surface, are eroded. Because of their small

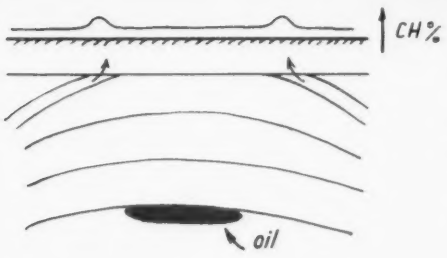

FIG. 5

depth, these are the ones which cause the anomalies even if their hydrocarbon concentration does not reach the exploitable level (Figure 4).

A similarly simple explanation may be given to the results of V. S. Kotov (1953), V. S. Sokolov (1958), and L. Horvitz (1957), according to which gas sampling in a greater depth of about 10 to 30 m yields better results than in a small depth (1–2 m). The near-surface layers are loose and possess high diffusion coefficients. Therefore, the deeper layers of small diffusion coefficient are unable to keep up a constant concentration gradient, and the gas concentration undergoes a sudden drop near the lower boundary of the loose layer (Figure 5). The prospecting for hydrocarbon gases coming from depth will therefore be more efficient beneath the loose layer.

I should like to remark, finally, that to establish full knowledge of gas migration, a similar analysis of gas effusion would be necessary. Unfortunately, the value of the constant k in Darcy's formula (1856) is not known for massive rocks, although in the oil industry an enormous number of permeabilites are determined. However, the methods employed there do not permit the determination of permeabilites below 10^{-4}–10^{-3} darcy, whereas that of the impermeable layers is presumably smaller than that by several orders of magnitude. The construction of an appropriate apparatus and the determination of permeabilites down to 10^{-13}–10^{-11} darcy, i.e. to the estimated order of magnitude of the impermeable layers, is planned at our Institute.

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GEOPHYSICS, VOL. XXVI, NO. 4 (AUGUST, 1961), PP. 452-464, 14 FIGS.

THE RESPONSE OF A DISK IN A DIPOLE FIELD*

ARTEL A. DOULOFF†

Abstract: Electromagnetic type curves are basic tools in mining geophysics in reducing ambiguity of interpretation. To this end, a mathematical solution is given for the quasi-static response of an infinitely conducting disk in a dipolar magnetic field. The solution, which emerges as a series solution of Laplace's equation in oblate spheroidal co-ordinates, converges rapidly enough only in certain ranges of radii of the disk. Sommerfeld's image method leads to an alternate solution that is exact. For finite conductivity, the mathematics becomes rather unwieldy, so experimental modelling produced the type curves in this range. By using high frequencies and aluminum disks, "infinitely" conducting models were constructed to check the theoretical solutions. All computation was done on an IBM 650 digital computer.

INTRODUCTION

Electromagnetic interpretation depends on the use of type curves of typical conductive bodies. To obtain additional curves, the particular body studied here is the circular disk. Although no known ore bodies are shaped like disks, this form was chosen for two main reasons. The first is that it is one of the few laminar bodies that can be treated mathematically. Laminar bodies are of particular interest to geophysicists as many of the important ore bodies occur in dyke-like form. Secondly, the infinite half-plane, which is a good approximation to a dyke, has been treated by West (1960), and by Wesley (1958), but has the one limitation of infinite strike and depth extent. It is of interest to observe the relation between the size of the body and the resulting anomaly, and this can be done with the disk.

Of the many different types of transmitter and receiver coil arrangements in general use today, the two types that will be studied here are (1) the transmitter and receiver both horizontal circular coils at the same elevation and (2) the transmitter a horizontal circular coil and the receiver a vertical coil at an elevation below that of the transmitter. The former system will be called the "ground" system and the latter, the "airborne" system.

ASSUMPTIONS

The theory is developed on the assumption that, at the low frequencies of electromagnetic prospecting (400 cps to 20 kc), Laplace's $\nabla^2\phi = 0$ can be used rather than Helmholtz' equation. This conclusion can be arrived at by considering Helmholtz' equation

$$\nabla^2\phi + (j\omega\mu\sigma - \omega^2\mu\epsilon)\phi = 0 \qquad (1)$$

where

ϕ is any scalar function,
ϵ is the dielectric constant,
ω is the angular frequency,
μ is the permeability,

and

σ is the conductivity.

The dielectric constant ϵ is very small compared to μ so that the $\omega^2\mu\epsilon$ term can be neglected at low frequencies. The conductivity of air is zero and of ground is fairly small. So $j\omega\mu\sigma$ can be taken as zero at low frequencies to a good approximation. Thus, we see that Helmholtz' equation reduces to Laplace's equation, outside the conductor. In practice, $j\omega\mu\sigma$ cannot always be neglected even at low frequencies, Canadian conditions being those for which it can most nearly be overlooked.

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† KCS Limited, Toronto, Ontario, Canada.

The basic assumptions employed in the development of the theory are that the charge density is zero and the disk has infinite conductivity.

ANALYSIS

The magnetic field, H, can be derived from a magnetic scalar potential as follows

$$H = -\nabla\phi_D. \tag{2}$$

ϕ_D can be defined as

$$\phi_D(x', y', z') = dl\cdot\nabla(1/R) \tag{3}$$

where dl is the dipole spacing and $1/R$ is the usual potential of a pole source. If dl is written as $\mathbf{i}dl_x+\mathbf{j}dk_y+\mathbf{k}dl_z$ and $1/R$ as ϕ_P then

$$H_n = -dl_n\nabla\frac{\partial}{\partial n}\phi_P, \quad n = x, y, \text{ or } z. \tag{4}$$

The geometrical and analytical problem of the circular disk is greatly simplified by the introduction of oblate spheroidal co-ordinates, Figure 1. In this co-ordinate system, we can specify a single value of one co-ordinate that gives exactly the desired surface, and no more, for the whole range of the remaining co-ordinates. This one co-ordinate will describe a spheroid which will degenerate into our desired disk as the value of that co-ordinate approaches zero. Thus, the application of the boundary conditions are simplified also as the conditions need satisfy one co-ordinate surface only. The common foci of all the hyperboloids and spheroids is $z=\pm a$, where the x axis is taken as the axis of revolution. Therefore, a focal circle of radius a, lying in the yz plane, represents our disk. The following relations hold between Cartesian and oblate spheroidal co-ordinates:

$$\begin{aligned} x &= a\xi\eta \\ y &= a[(1+\xi^2)(1-\eta^2)]^{1/2}\cos\theta \\ z &= a[(1+\xi^2)(1-\eta^2)]^{1/2}\sin\theta \end{aligned}$$

where ξ, η, and θ are the parameters of the spheroids, hyperboloids, and planes respectively, with their ranges given by

$$0 \le \theta \le 2\pi, \quad 0 \le \xi \le \infty, \quad -1 \le \eta \le 1.$$

In this system $\Delta^2\phi=0$ is written

$$\frac{\partial}{\partial\eta}\left[(1-\eta^2)\frac{\partial\phi}{\partial\eta}\right]+\frac{\partial}{\partial\xi}\left[(1+\xi^2)\frac{\partial\phi}{\partial\xi}\right]$$

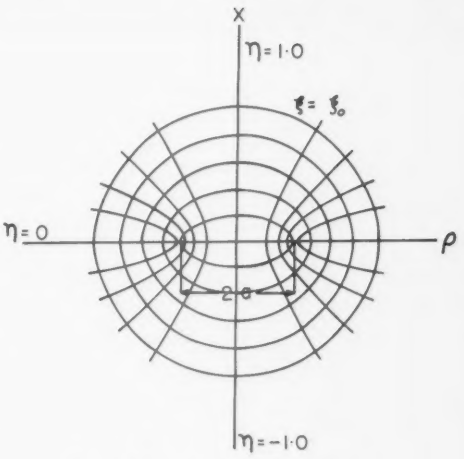

FIG. 1. Oblate spheroidal co-ordinates.

$$+\frac{\eta^2+\xi^2}{(1+\xi^2)(1-\eta^2)}\frac{\partial^2\phi}{\partial\theta^2}=0. \tag{5}$$

By the usual methods of separation of variables we obtain the most general solution

$$\phi = \sum_{n=0}^{\infty}\sum_{m=0}^{n}[A_{mn}P_n^m(\eta)+B_{mn}Q_n^m(\eta)] \cdot[A_{mn}'P_n^m(j\xi)+B_{mn}'Q_n^m(j\xi)]e^{\pm im\theta}. \tag{6}$$

$P_n^m(x)$ and $Q_n^m(x)$ are Associated Legendre Functions of the first and second kind, respectively. The solution must approach zero as $t\to\infty$ (condition of regularity), and thus $P_n^m(j\xi)$ is rejected from the solution as it becomes infinite with ξ. $A_{mn}'=0$. $Q_n^m(\eta)$ is rejected from the solution as it has infinities at $\eta=\pm1$. Therefore, $B_{mn}=0$. In order that the solution be single valued, m and n are taken as positive integers or zero, with $m\le n$. Thus, the expression for the total potential, written as the sum of the primary and secondary potentials, is given as

$$\phi(\xi,\eta,\theta) = \frac{K}{4\pi}\frac{1}{R}+\sum_{n=0}^{\infty}\sum_{m=0}^{n}[A_{mn}''\cos m\theta + B_{mn}''\sin m\theta]P_n^m(\eta)Q_n^m(j\xi), \tag{7}$$

where K is the pole strength.

We apply the boundary condition that on the surface of the spheroid the normal component of the magnetic field must vanish, i.e.

$$\frac{\partial \phi}{\partial \xi} = 0 \quad \text{at} \quad \xi = \xi_s. \tag{8}$$

Applying the boundary conditions and writing $1/R$ in oblate spheroidal co-ordinates, we get

$$\frac{K}{4\pi} \sum_{n=0}^{\infty} \sum_{m=0}^{n} M_{mn} P_n^m(\eta) P_n^m(\eta_0) Q_n^m(j\xi_0) P_n'^m(j\xi_s) [\cos m\theta_0 \cos m\theta + \sin m\theta_0 \sin m\theta]$$

$$+ \sum_{n=0}^{\infty} \sum_{m=0}^{n} [A_{mn}'' \cos m\theta + B_{mn}'' \sin m\theta] P_n^m(\eta) Q_n'^m(j\xi_s) = 0 \tag{9}$$

where

$$M_{mn} = \frac{j(2n+1)(2-\delta_m^0)}{a(-1)^m} \left[\frac{(n-m)!}{(n+m)!}\right]^2$$

and δ_m^0 is the Kronecker delta, which has the properties

$$\delta_m^0 = \begin{cases} 1, & m = 0 \\ 0, & m \neq 0. \end{cases}$$

Equating the coefficients of the cosine and sine terms respectively gives the value of A_{mn}'' and B_{mn}'',

$$A_{mn}'' = \frac{-K}{4\pi} M_{mn} P_n^m(\eta_0) Q_n^m(j\xi_0) \frac{P_n'^m(j\xi_s)}{Q_n'^m(j\xi_s)} \cos m\theta_0, \tag{10a}$$

$$B_{mn}'' = \frac{-K}{4\pi} M_{mn} P_n^m(\eta_0) Q_n^m(j\xi_0) \frac{P_n'^m(j\xi_s)}{Q_n'^m(j\xi_s)} \sin m\theta_0. \tag{10b}$$

Substituting equation (10) into equation (9) gives the final solution for the potential of a perfectly conducting spheroid in the presence of a magnetic pole,

$$\phi(\xi, \eta, \theta) = \frac{K}{4\pi} \left[\frac{1}{R} - \sum_{n=0}^{\infty} \sum_{m=0}^{n} M_{mn} P_n^m(\eta_0) P_n^m(\eta) Q_n^m(j\xi_0) Q_n^m(j\xi) \frac{P_n'^m(j\xi_s)}{Q_n'^m(j\xi_s)} \cos m(\theta - \theta_0)\right]. \tag{11}$$

This is the required ϕ_P of equation (4). This result is similar to that obtained by Khalfin (1956), and Cook and Van Nostrand (1954) for the resistivity case.

To obtain the corresponding potential for the disk, we let $\xi_s \to 0$. The only change in ϕ_P then is that the expression

$$\frac{P_n^{m\prime}(j\xi_s)}{Q_n'^m(j\xi_s)} = \begin{cases} j\left(\frac{\pi}{2}\right)^{-1} & \text{for } (n+m) \text{ odd} \\ 0 & \text{for } (n-m) \text{ even.} \end{cases}$$

To calculate the potential of the dipole field, ϕ_P is differentiated with respect to the source position. As an example we will consider the "ground" system, with the transmitter and receiver both horizontal coils, passing over a vertical disk. All measurements have been confined to the plane $\theta = 0$ such that $z = z_0$, i.e. we are considering perpendicular traverses only. For this case, ϕ_P becomes,

$$\phi_P = \frac{K}{4\pi} \left[\frac{1}{R} - \sum_{n=0}^{\infty} \sum_{m=0}^{n} N_{mn} P_n^m(\eta) Q_n^m(j\xi) Q_n^m(j\xi_0) P_n^m(\eta_0)\right]. \tag{12}$$

The potential for a vertical dipole will then be

$$\frac{\partial \phi_P}{\partial y_0} = \frac{Kdl_y}{4\pi}\left[\frac{y - y_0}{R^3} + A_0 \sum_{n=0}^{\infty}\sum_{m=0}^{n} N_{mn} P_n^m(\eta) Q_n^m(j\xi) Q_n^m(j\xi_0) P_n'^m(\eta_0)\right.$$
$$\left. - B_0 \sum_{n=0}^{\infty}\sum_{m=0}^{n} N_{mn} P_n^m(\eta) Q_n^m(j\xi) Q_n'^m(j\xi_0) P_n^m(\eta_0)\right] \tag{13}$$

where

$$A_0 = \sqrt{2} x_0 y_0 F_0^3 G_0, \qquad B_0 = \frac{j y_0 F_0 G_0}{\sqrt{2}a},$$

$$F_0 = (\sqrt{(x_0^2 + y_0^2 - a^2) + \sqrt{(x_0^2 + y_0^2 - a^2) + 4a^2 x_0^2}})^{-1}$$

$$G_0 = \left(1 + \frac{x_0^2 + y_0^2 - a^2}{\sqrt{(x_0^2 + y_0^2 - a^2) + 4a^2 x_0^2}}\right),$$

$$R = \sqrt{(x - x_0)^2 + (y - y_0)^2}$$

To obtain the magnetic field for the "ground" system, vertical disk, the dipole potential is differentiated with respect to the position of the point of observation. The transmitter and receiver will be considered at the same elevation i.e. $y = y_0$.

$$\therefore\ H_y = \frac{Kdl_y}{4\pi}\frac{\partial^2 \phi_P}{\partial y \partial y_0} = \frac{Kdl_y}{4\pi}\frac{1}{R^3}$$
$$- A_0\sqrt{2} xy F^3 G \sum_{n=0}^{\infty}\sum_{m=0}^{n} N_{mn} P_n'^m(\eta) Q_n^m(j\xi) Q_n^m(j\xi_0) P_n'^m(\eta_0)$$
$$+ A_0 jyFG/\sqrt{2}a \cdot \sum_{n=0}^{\infty}\sum_{m=0}^{n} N_{mn} P_n^m(\eta) Q_n'^m(j\xi) Q_n^m(j\xi_0) P_n'^m(\eta_0)$$
$$+ B_0\sqrt{2} xy F^3 G \sum_{n=0}^{\infty}\sum_{m=0}^{n} N_{mn} P_n'^m(\eta) Q_n^m(j\xi) Q_n'^m(j\xi_0) P_n^m(\eta_0)$$
$$- B_0 jyFG/\sqrt{2}a \cdot \sum_{n=0}^{\infty}\sum_{m=0}^{n} N_{mn} P_n^m(\eta) Q_n^{m\prime}(j\xi) Q_n'^m(j\xi_0) P_n^m(\eta_0) \tag{14}$$

The quantity of interest in geophysics is the ratio of the secondary to primary fields. The first term on the right side of the solution gives the primary field while the rest of the solution, given in the four terms of double summations, is the secondary field. The other components are derived similarly. It is a simple matter to resolve the components in the desired direction for an arbitrarily dipping body.

COMPUTATION

All computation was done on an IBM 650, partly at the University of Toronto and partly at KCS Limited. The only problems involved in the computation were the calculation of the Associated Legendre Functions and the determination of the convergence of the infinite series.

The Legendre Functions were calculated by first computing key values for the lower order functions and then using recursion formulae. Convergence of the series was investigated experimentally on the computer rather than ana-

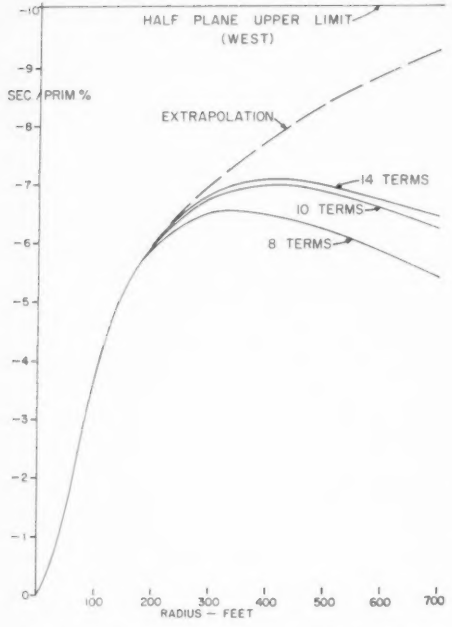

FIG. 2. Maximum anomaly plotted against radius for various terms of the series solution.

lytically. Figure 2 shows the maximum anomaly plotted against the radius of the disk for eight, ten, and fourteen terms. From this graph, it is evident that convergence is slow. The apparent reversal at a radius of about 300 ft is caused by the increasing slowness of convergence of the series as the coils' elevation becomes small compared to the radius of the disk. If enough terms of the series were taken, the curve would eventually approach asymptotically, for large radii, the value for the half-plane obtained by West (1960). This was not practical on the computer available. However, the solution as presently computed is valid up to a radius of 300 ft; and for all practical purposes, for larger radii, the half-plane solution would suffice.

Figures 3, 4, and 5 are samples of the output of the computation of type curves for the disk. Many more type curves were produced for variations of the parameters but have not been included here.

EXPERIMENTAL RESULTS

Scale model experiments were set up to validate the theoretical curves and to produce type curves in the finite conductivity range for which no theoretical solution exists. Aluminum disks of thickness 0.051 inch, conductivity 23.8×10^6 mhos/meter and diameters of one, two, three, and four ft were used to model the infinite conductivity range at a frequency of 20,000 cps.

Figure 6 compares experimental and theoretical data for the vertical disk, using the ground system. The agreement is excellent with the theoretical curve being slightly less in magnitude (2.5 percent) than the experimental because of the termination of the series solution. Figure 7 shows similar results for the horizontal disk using the "ground" system. Agreement is not quite as good here at the peak which may be partly explained by experimental error. Again, corroboration of theoretical and experimental data is seen in Figure 8 for the vertical disk, using the airborne system.

Figure 9 illustrates how the solution fails for the horizontal disk of 300-ft radius with an "airborne" system passing over at an elevation of 400 ft. A fairly good fit is obtained on the flanks of the anomaly, but a large oscillation occurs at the center of the theoretical curve that doesn't exist experimentally. The discrepancy again shows here because the elevation of the coils becomes small compared to the radius of the disk. In Figure 10 the discrepancy disappears when we consider a smaller disk at a greater depth.

Figure 11 compares the experimental disk results for a radius of 600 ft with the half plane results of West (1960). This again illustrates the similar response between the two in magnitude and shape.

FINITE CONDUCTIVITY

All the work up till now has considered only infinite conductivity and hence only in-phase response. In reality we never get this picture but will generally have a quadrature, or out-of-phase component due to finite conductivity, with the relative magnitude of in-phase and quadrature being a measure of conductivity. For finite conductivity, the nonmagnetic stainless steel disks of thickness 0.050 inch, conductivity 1.43×10^6 mhos/meter, and diameters of one-half, one, two, three, and four ft were used.

Figure 12 illustrates maximum response curves obtained for a vertical disk, "ground" system using a disk radius of 800 ft and depth of 50 ft. $\mu=4\pi\times10^{-7}$, l is the coil separation, and s the

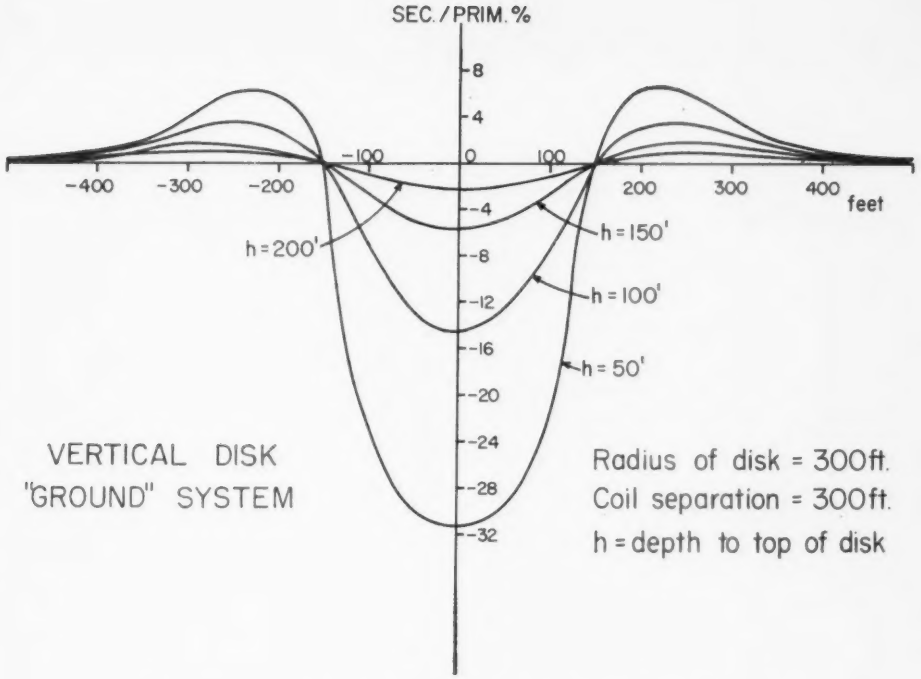

FIG. 3. Theoretical response of a vertical disk ground system for various depths.

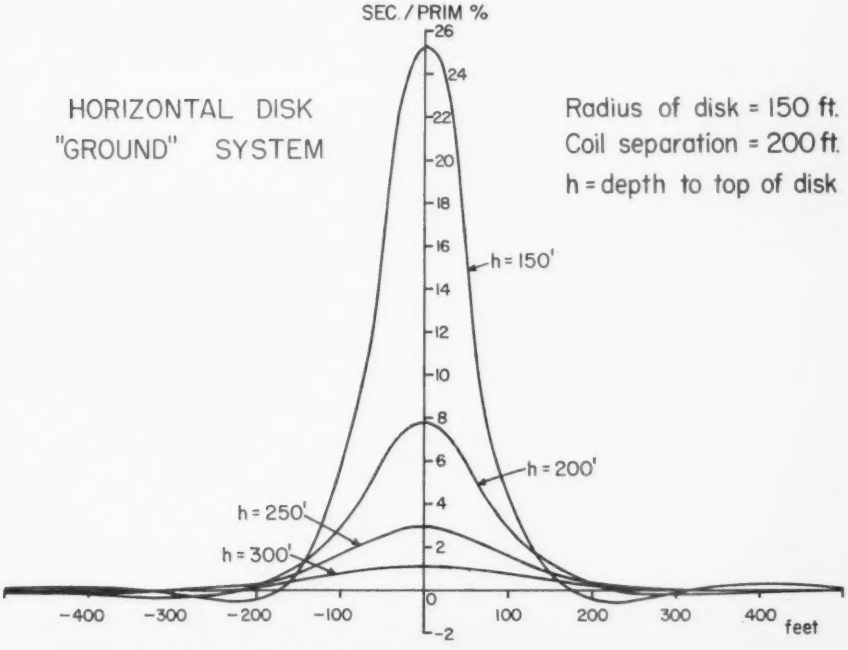

FIG. 4. Theoretical response of a horizontal disk ground system for various depths.

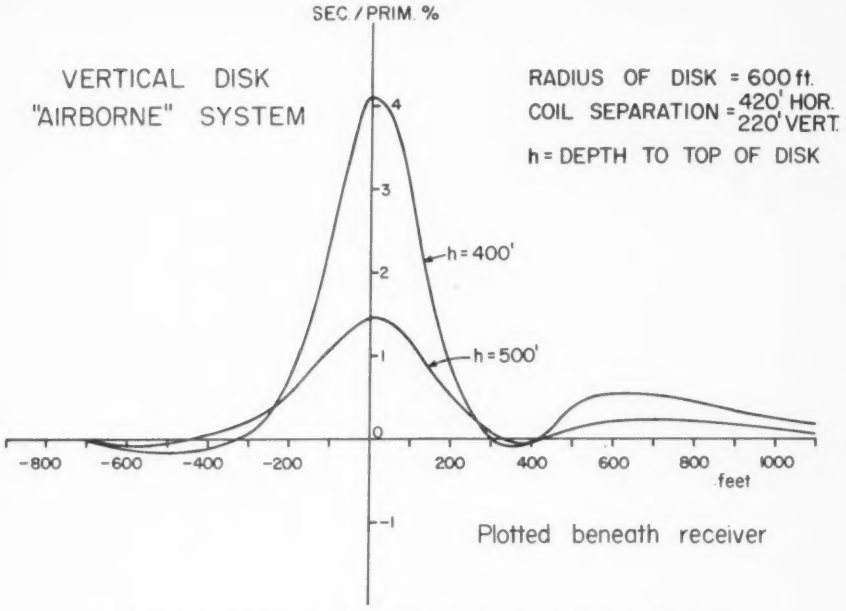

FIG. 5. Theoretical response of a vertical disk airborne system for various depths.

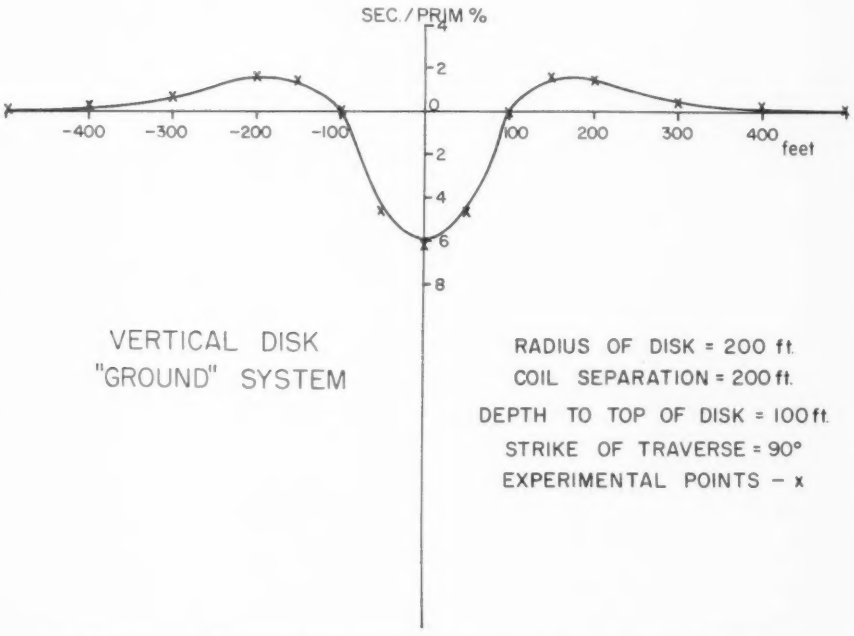

FIG. 6. Comparison of theoretical and experimental traverses for a vertical disk ground system.

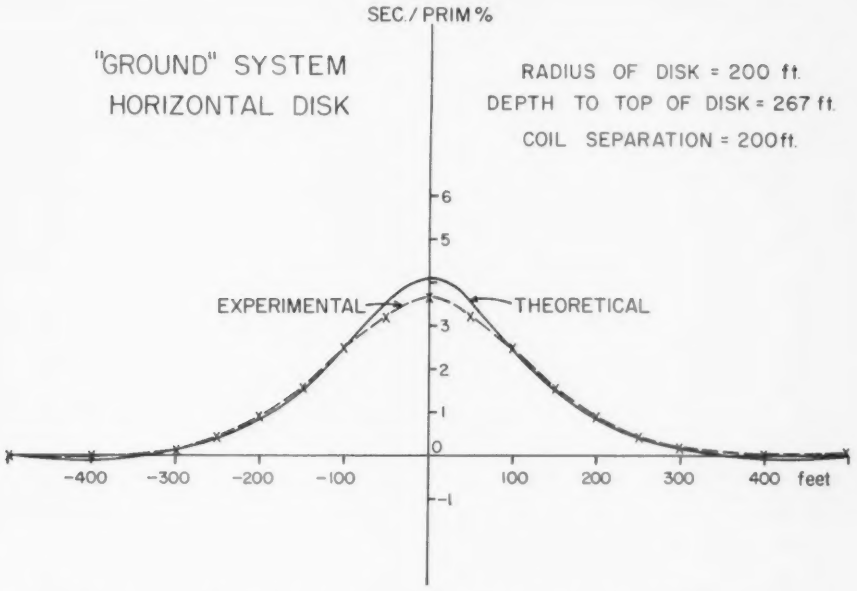

FIG. 7. Comparison of theoretical and experimental traverses for a horizontal disk ground system.

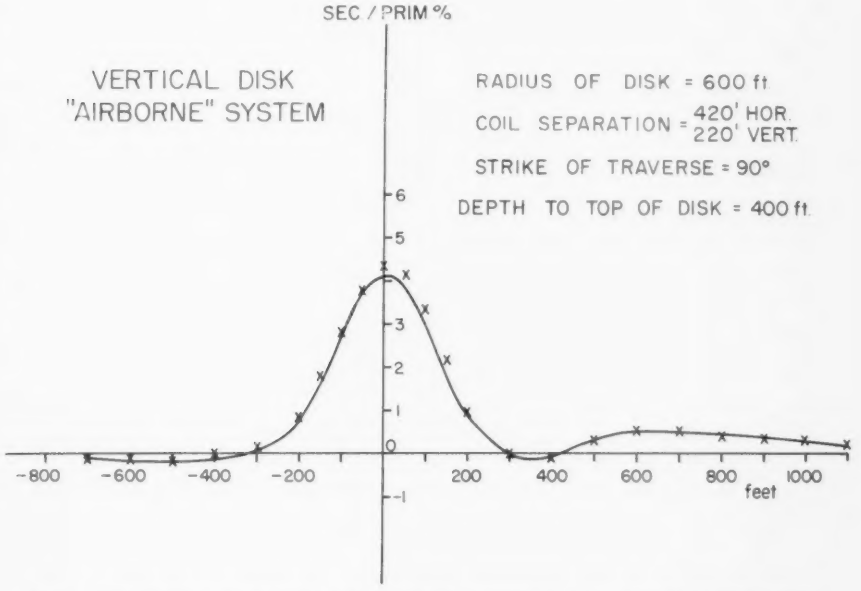

FIG. 8. Comparison of experimental and theoretical traverses for a vertical disk airborne system.

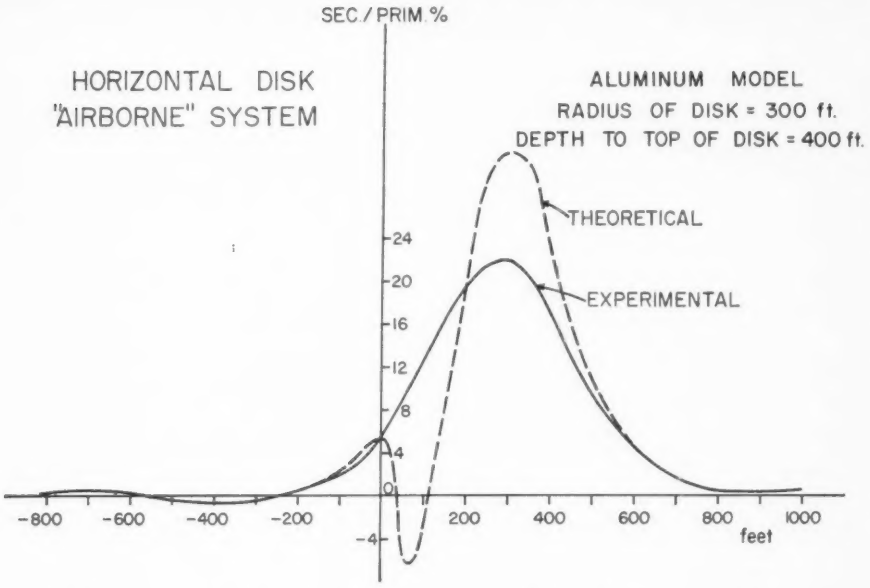

FIG. 9. Comparison of theoretical and experimental traverses for an airborne system passing over a horizontal disk of radius 300 ft and depth of 400 ft.

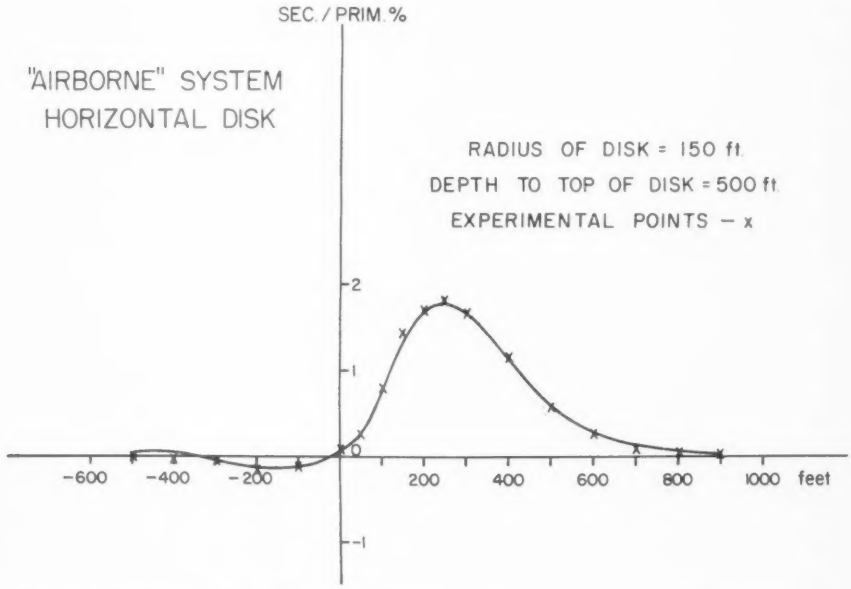

FIG. 10. Comparison of theoretical and experimental traverses for an airborne system passing over a horizontal disk of radius 150 ft and depth of 500 ft.

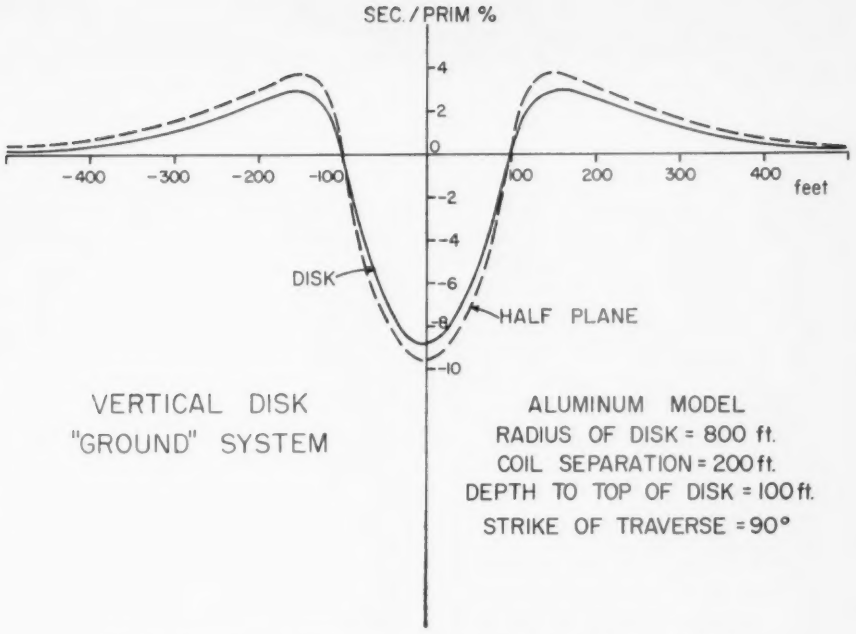

FIG. 11. Comparison of experimental results for a disk of radius 800 ft and the half plane results of West (1960).

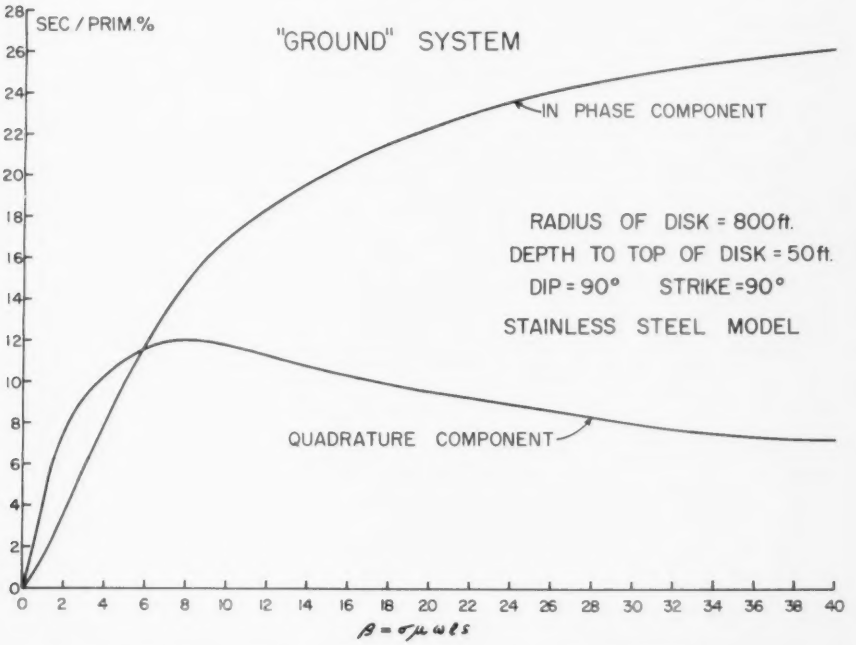

FIG. 12. Maximum in-phase and quadrature response curves for a vertical disk ground system.

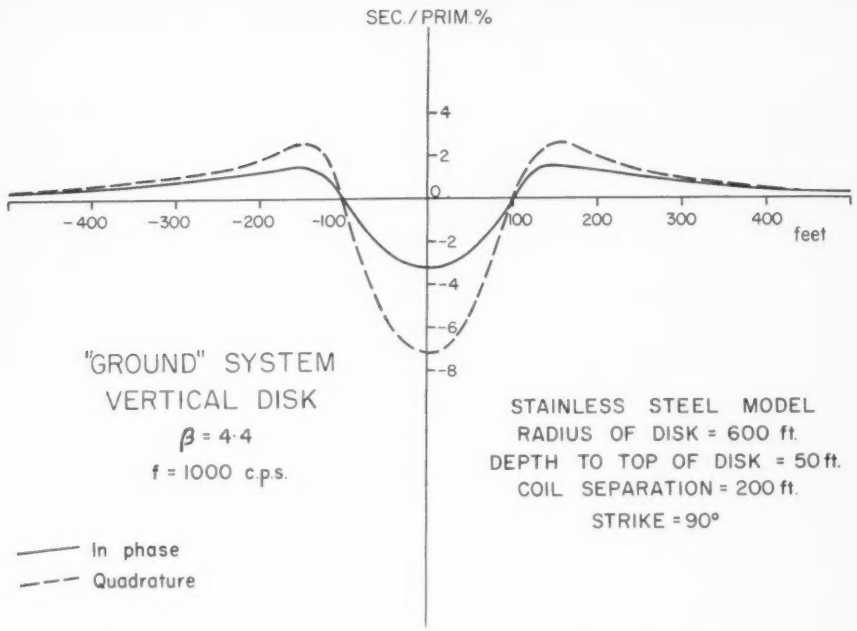

FIG. 13. Finite conductivity profiles for a vertical disk ground system using a frequency of 1,000 cps.

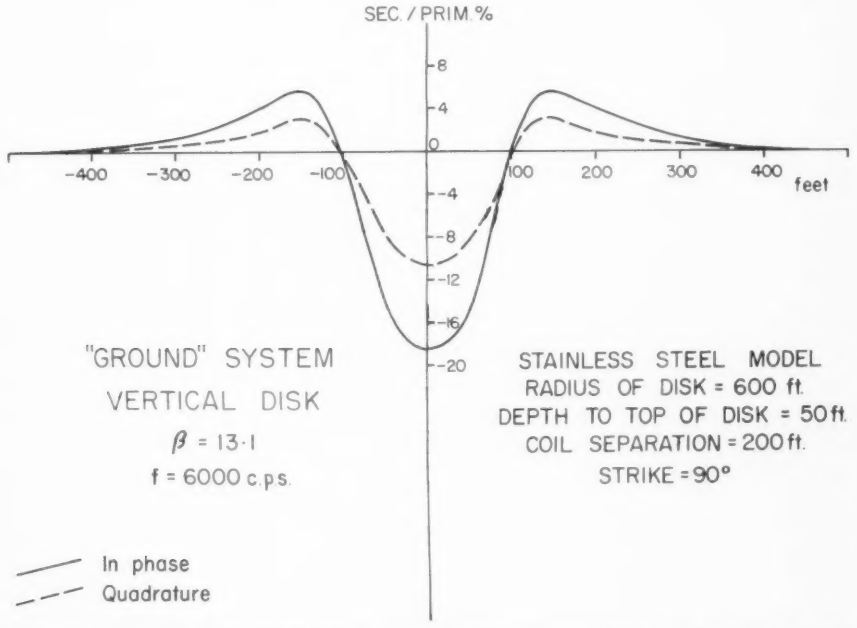

FIG. 14. Finite conductivity profiles for a vertical disk ground system using a frequency of 6,000 cps.

thickness of the conductor. With everything being kept constant, the frequency was varied from 500 cps to 20,000 cps to give the complete relations between peak in-phase and quadrature responses. From these curves, two frequencies of 6,000 cps and 1,000 cps were chosen to produce type curves in both good conductor and poor conductor ranges.

In Figure 14 we see one example of the type curve obtained using a frequency of 6,000 cps for a disk of radius 400 ft and depth of 50 ft. The in-phase component exceeds the quadrature component by a ratio of 2:1. Figure 13 illustrates the same physical situation except that the lower frequency of 1,000 cps was used, showing the quadrature exceeding the in-phase by a ratio 2:1.

ALTERNATE SOLUTION

There is an alternate method to obtain the solution for the disk of infinite conductivity. It is based on Ashour's (1952) solution for a pole source which is itself based on Jeans' (1900) application of Sommerfeld's (1897) multiform potential theory to the semi-infinite plane. The solution is an exact solution with no convergence problem, containing trigonometric functions only. A brief summary of Jeans' theory will be discussed.

A Riemann space of two regions is constructed with the first region identified with the space containing the magnetic system and the second to contain certain images of this system. The field of these images will represent the induced field. Sommerfeld showed that the Newtonian potential due to a single pole at (x, y, z) in the first region is equal to the sum of the Riemann potentials of two similar poles, one at (x, y, z) and the other at (x', y', z') in the second region. Let Ω be the magnetic potential of the currents induced in the sheet by the sudden introduction of a pole at (x, y, z). Then, if $P(x, y, z)$ is its Riemann potential, Jeans found that

$$\Omega = P(x', y', -z') - P(x', y', z'). \quad (15)$$

The problem now is to evaluate the Riemann potential for the disk. To do this, toroidal coordinates (ψ, σ, θ) will be used that are defined by

$$x = \rho \cos\theta, \qquad y = \rho \sin\theta,$$

$$\rho = \frac{a \sinh\sigma}{\cosh\sigma - \cos\psi}, \qquad z = \frac{a \sin\psi}{\cosh\sigma - \cos\psi}.$$

The surfaces $\psi =$ constant are the spherical caps having the circle $z=0$, $x^2+y^2=a^2$ in common. If we consider a double space in which a disk forms the principal "boundary," the value ψ is discontinuous by 2π in passing from one region to the other through this principal disk, i.e.

$$-\pi < \psi < \pi \quad \text{in the first region, and}$$

$$\pi < \psi < 3\pi \quad \text{in the second.}$$

Corresponding to a point (ψ, σ, θ) in the first region, there is an associated point $(\psi+2\pi, \sigma, \theta)$ in the second.

The ordinary Newtonian potential at (ψ, σ, θ) due to a magnetic pole of unit strength situated at $(\psi_0, \sigma_0, \theta_0)$ is given by Bateman (1931).

$$\frac{1}{R} = \sqrt{(\cosh\sigma - \cos\psi)(\cosh\sigma_0 - \cos\psi_0)} \int_{-\infty}^{\infty} \frac{\sinh u(\cosh u - \cosh\alpha)}{\cosh u - \cos(\psi - \psi_0)}\, du \quad (16)$$

where

$$\cosh\alpha = \cosh\sigma \cosh\sigma_0 - \sinh\sigma \sinh\sigma_0 \cos(\theta - \theta_0).$$

Using the identity

$$2 \sinh u[\cosh u - \cos(\psi - \psi_0)]^{-1} = \sinh \tfrac{1}{2}u\left[\left\{\cosh \tfrac{1}{2}u - \cos \tfrac{1}{2}(\psi - \psi_0)\right\}^{-1} + \left\{\cosh \tfrac{1}{2}u + \cos \tfrac{1}{2}(\psi - \psi_0)\right\}^{-1}\right], \quad (17)$$

Bateman shows that

$$\frac{1}{R} = P(\psi_0, \sigma_0, \theta_0) + P(\psi_0 + 2\pi, \sigma_0, \theta_0) \quad (18)$$

where

$$P(\psi_0, \sigma_0, \theta_0) = \frac{1}{R}\left[\frac{1}{2} + \frac{1}{\pi} \sin^{-1}\left\{\cos \tfrac{1}{2}(\psi - \psi_0) \operatorname{sech} \tfrac{1}{2}\alpha\right\}\right].$$

It is seen that the expression for the Newtonian potential satisfies the Sommerfeld condition for the Riemann potentials as stated above.

We can now write, according to Jeans' solution,

$$\Omega = P(-\psi_0 + 2\pi, \sigma_0, \theta_0) - P(\psi_0 + 2\pi, \sigma_0, \theta_0). \quad (19)$$

Ω can be identified with ϕ_P of equation (4), and thus the magnetic field can be found accordingly.

ACKNOWLEDGMENTS

The author would like to express deepest appreciation to Dr. F. S. Grant and Dr. G. F. West of the University of Toronto for their many helpful suggestions and encouragements throughout the course of this work, and to KCS Limited for use of their computer in the latter stages of computation.

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GEOPHYSICS, VOL. XXVI, NO. 4 (AUGUST, 1961), PP. 465-473, 12 FIGS.

MAGNETO-TELLURIC SOUNDING THREE-LAYER INTERPRETATION CURVES*

S. H. YUNGUL†

Abstract: To interpret the magneto-telluric sounding data in terms of layering in the subsurface, one needs a catalog of "standard" curves. The purpose of this paper is to present such a catalog for the three-layer cases.

The calculations were done by incorporating the formulas given by Cagniard (1953) into a digital computer program.

The catalog consists of 117 apparent-resistivity-vs-period curves representing ten resistivity combinations. In each case the third, semi-infinite medium represents the "basement" with infinite resistivity. In addition, a set of two-layer curves for the total range of resistivity combinations is also given.

The procedure in using the curves is briefly explained.

INTRODUCTION

The method of magneto-telluric sounding makes use of the natural electromagnetic waves which are practically continuously generated (the geomagnetic "pulsations," for instance, and the telluric currents associated with them). The objective is to obtain, so to speak, crude electrical resistivity logs without drilling. As the name implies, each observation yields downward information at one point on the surface of the earth. The theory is based on the geologic assumption that the subsurface is made of horizontal layers of infinite extent, each being electrically homogeneous and isotropic. The method involves simultaneous recordings of the telluric (electric) field $E_x(t)$ and the magnetic field $H_y(t)$ at one point of the surface of the earth which is designated by the x-y plane.

The theory and practice of the method was developed by Cagniard (1953). The interpretation of the field data matches the experimental curve (apparent resistivity vs period) with a standardized theoretical curve of the same nature. Thus, one needs a catalog of standard curves. Cagniard (1953) presented a family of two-layer curves. Tikhonov (1956) published a few three-layer curves. The purpose of this paper is to supply the reader with a sufficient amount of three-layer curves so that he can actually interpret the field data.

The models for which the curves are given here are the same as those for which the Compagnie Générale de Géophysique of France (1955) published a catalog of direct current resistivity sounding curves. Furthermore, in each case the deepest medium is an insulator representing the "basement."

COMPUTATIONS

Figure 1 shows the model. The standardization is the same as Cagniard's (1953); that is, the resistivity and the thickness of the upper layer, $\bar{\rho}_1$ and $\bar{h}_1$ respectively, are fixed, one ohm-meter and one kilometer. In addition, $\bar{\rho}_3$ is infinite in each case. Thus, $\bar{\rho}_2$ and $\bar{h}_2$ are the two variables. Each family of curves corresponds to one $\bar{\rho}_2$ and various $\bar{h}_2$ values. The following values of $\bar{\rho}_2$ in ohm-meters were used: 1/39, 1/19, 1/9, 1/4, 3/7, 2/3, 3/2, 7/3, 4, and 9. On each figure the three-layer model is shown at the upper-left corner. (The number at the top, such as 81, is that used by the Compagnie Générale de Géophysique to designate the resistivity combination, and "C" stands for California Research Corporation.) In each family, $\bar{h}_2$ ranges between one km and ∞. A suitable sequence of $\bar{h}_2$ values is taken, the largest finite one being 25 km. When $\bar{h}_2 = 1$ km, the thickness of the inner layer, $\bar{h}_2 - \bar{h}_1$, becomes zero and the problem reverts to a two-layer case. The small number given on each curve is the value of $\bar{h}_2$ in kilometers.

A program for the IBM 704 computer, written

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† California Research Corporation, La Habra, California. Present address: A. & M. College of Texas, Dept. of Geology and Geophysics, College Station, Texas.

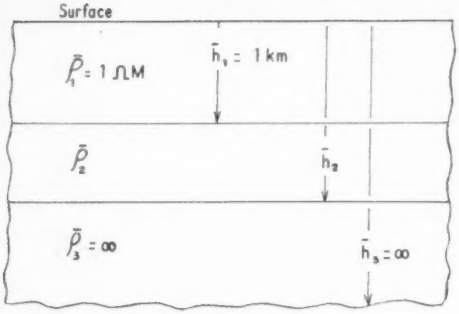

FIG. 1. Magneto-telluric, standard model.

by Dr. R. J. Runge of California Research Corporation, was used to calculate the apparent resistivity $\bar{\rho}_A$ in ohm-meters for specified periods $\overline{T}$ in seconds.

Each curve was drawn from 50 points. The periods $\overline{T}$ used were ten equal spacings in the intervals 0.1 to 1 sec, 1 to 10 sec, 10 to 100 sec, 100 to 1,000 sec, and 1,000 to 10,000 sec.

In each family, the curves for $\bar{h}_2 = 1$ and $\bar{h}_2 = \infty$ are the two-layer cases, and they pass through a common point A whose co-ordinates are $\bar{\rho}_A = 1$ ohm-meter and $\overline{T} = 6.4$ sec.

Figure 2 is a set of two-layer curves in which $\bar{\rho}_A$ is plotted against $\overline{T}$. These curves were also computed by the IBM 704 program mentioned above. Figures 3 through 12 are the three-layer curves.

PRACTICAL USE OF THE CURVE

Cagniard (1953) completely explained the practical use of the theoretical curves. However, for the sake of continuity, the procedure of interpreting the experimental curves will be briefly explained in the following:

Let us define a standard model by the quantities $\bar{\rho}_1$, $\bar{\rho}_2$, $\bar{\rho}_3$, $\bar{h}_1$, and $\bar{h}_2$, and consider the apparent resistivity $\bar{\rho}_A$ for a certain period $\overline{T}$. On the other hand, let us define a certain actual model by the quantities ρ_1, ρ_2, ρ_3, h_1, and h_2, and consider the apparent resistivity ρ_A for a certain period T in such a way that these quantities are related to the standard model by means of the proportionality factors ρ, h, and τ in the following way:

$$\rho_1/\bar{\rho}_1 = \rho_2/\bar{\rho}_2 = \rho_3/\bar{\rho}_3 = \rho,$$
$$h_1/\bar{h}_1 = h_2/\bar{h}_2 = h,$$
$$T/\overline{T} = \tau. \qquad (1)$$

According to the law of electrodynamic similitude, if

$$h^2 = \rho\tau$$

the solution of Maxwell's equations for the standard model is also a solution for the actual model. It follows that

$$\rho_A = \rho\bar{\rho}_A, \qquad (2)$$

and ρ_A is relative to a period such that

$$\tau = h^2/\rho. \qquad (3)$$

The experimental apparent resistivities are calculated by means of the following equation:

$$\rho_A = 0.2T(E_x/H_y)^2, \qquad (4)$$

where ρ_A is in ohm-meters, T in seconds, E_x in millivolts per kilometer, and H_y in gammas. The latter two quantities are the amplitudes. The $\rho_A(T)$ function is plotted on the same logarithmic paper used for the standard curves. By means of translation motions, a match between the experimental curve $\bar{\rho}_A(T)$ and a certain standard curve $\bar{\rho}_A(\overline{T})$ is obtained. The interpretation is as follows:

(1) *Two-layer curves.* According to equation (2), the horizontal line $\bar{\rho}_A = 1$ reads ρ_1 on the experimental ρ_A-axis, and $\rho_2 = \bar{\rho}_2\rho_1$, where $\bar{\rho}_2$ is indicated on the standard model. The vertical line $\overline{T} = 1$ reads a certain value T_1 on the experimental T-axis. According to equation (3), we have

$$h_1 = \sqrt{T_1\rho_1}.$$

Or, if the vertical ine $\overline{T} = 10$ is used, we have

$$h_1 = \sqrt{\rho_1 T_{10}/10}.$$

(2) *Three-layer curves.* ρ_1, ρ_2, and h_1 are determined as explained for the two-layer case. The values of $\bar{\rho}_1$, $\bar{\rho}_3$, and $\bar{h}_2$ are indicated by the standard curve. Then, according to equations (1) we have

$$\rho_3 = \bar{\rho}_3\rho_1,$$
$$h_2 = \bar{h}_2 h_1.$$

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The writer wishes to acknowledge that the major part of the effort in publishing this paper is attributable to Dr. R. J. Runge of California Re-

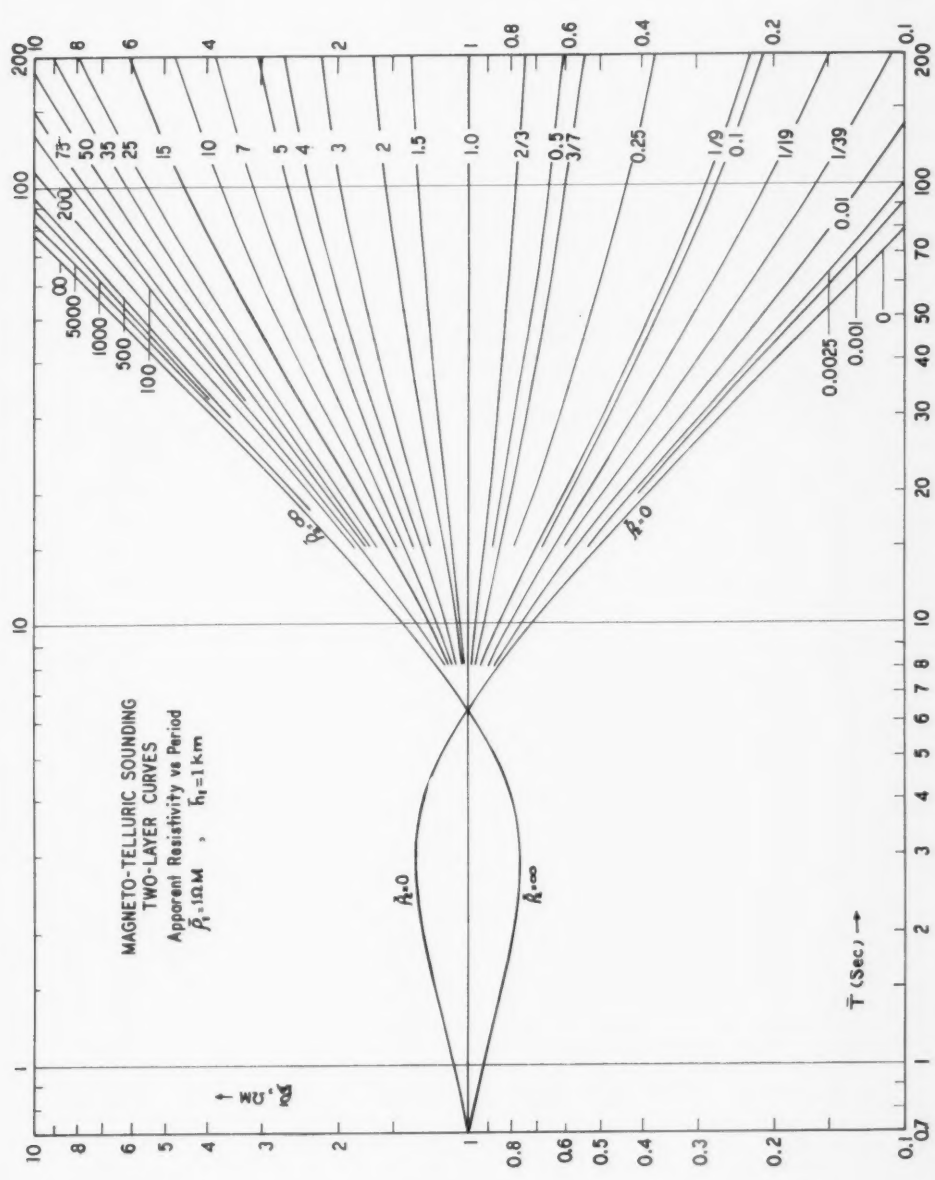
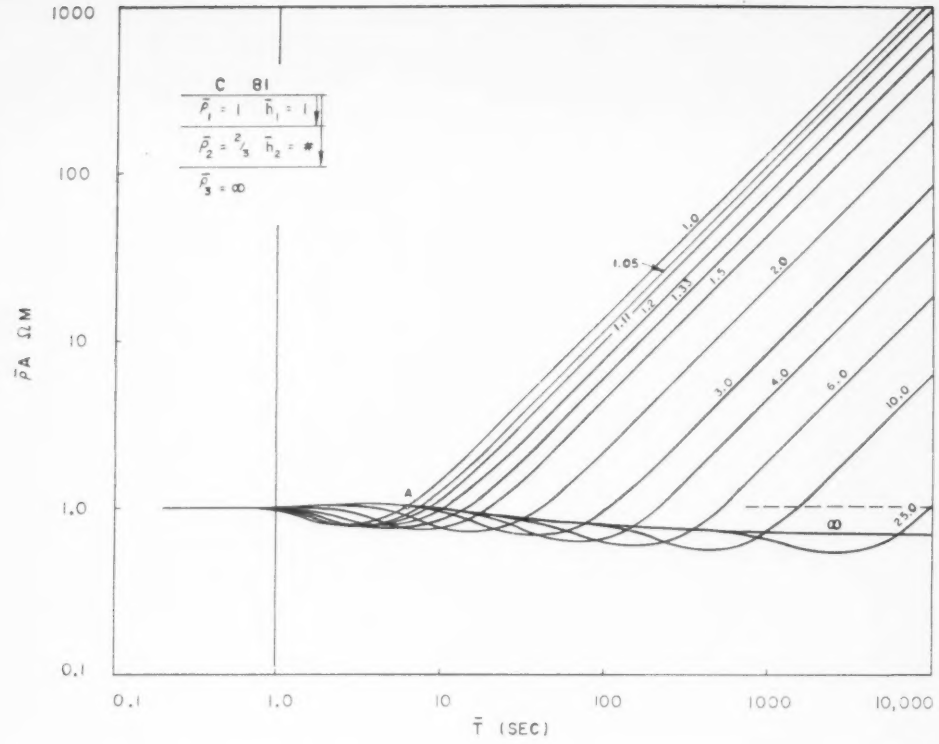


FIG. 2. Magneto-telluric, two-layer standard curves.



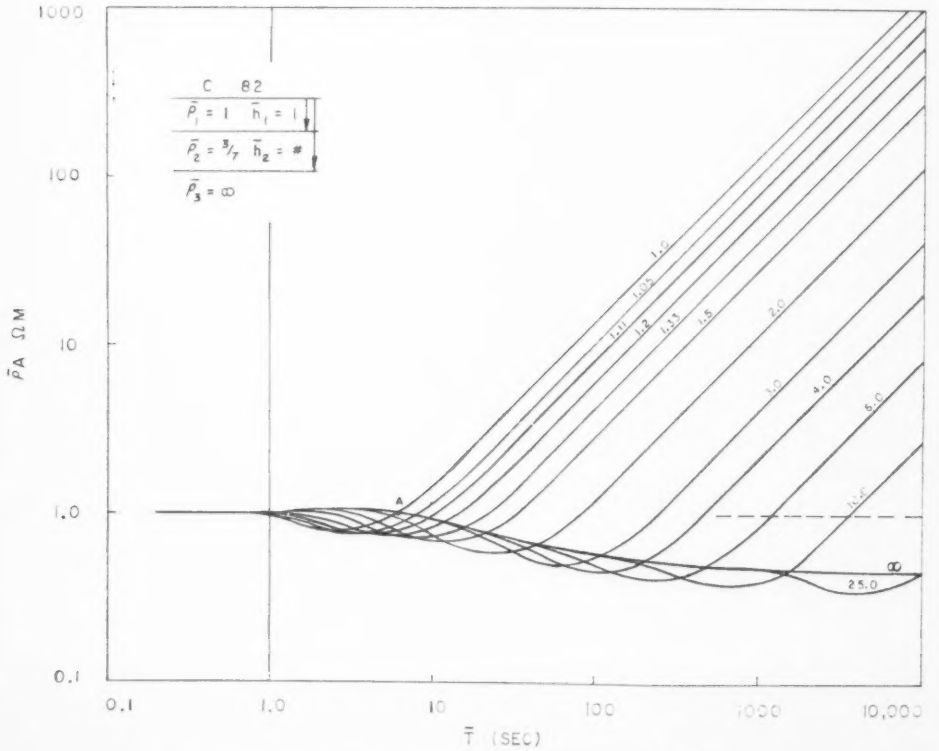
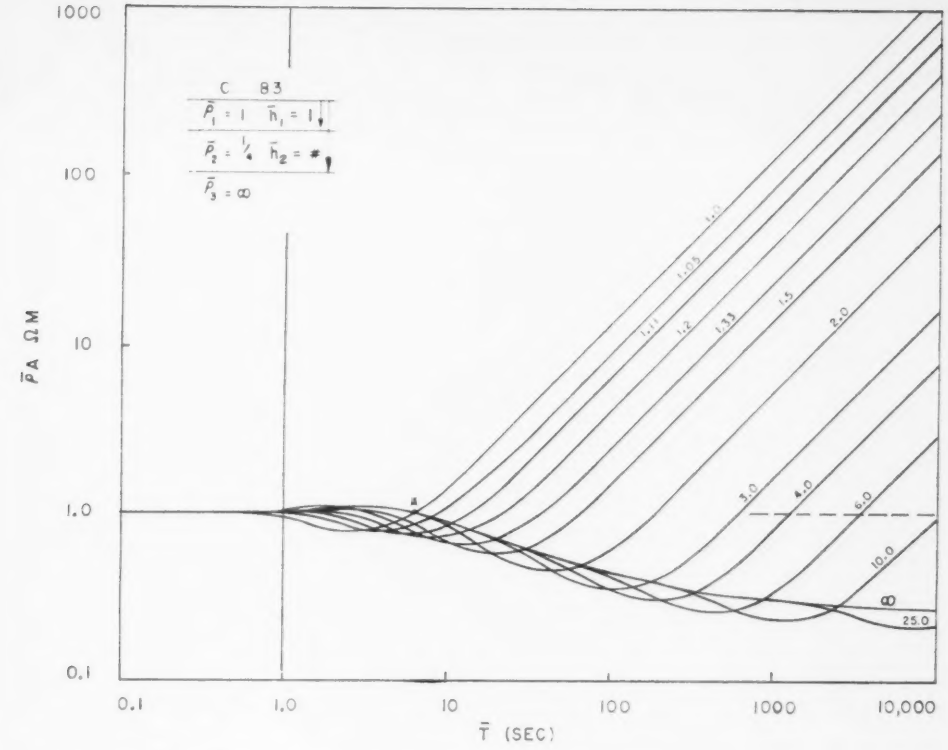


FIG. 3 (above) and 4 (below). Magneto-telluric, three-layer standard curves.



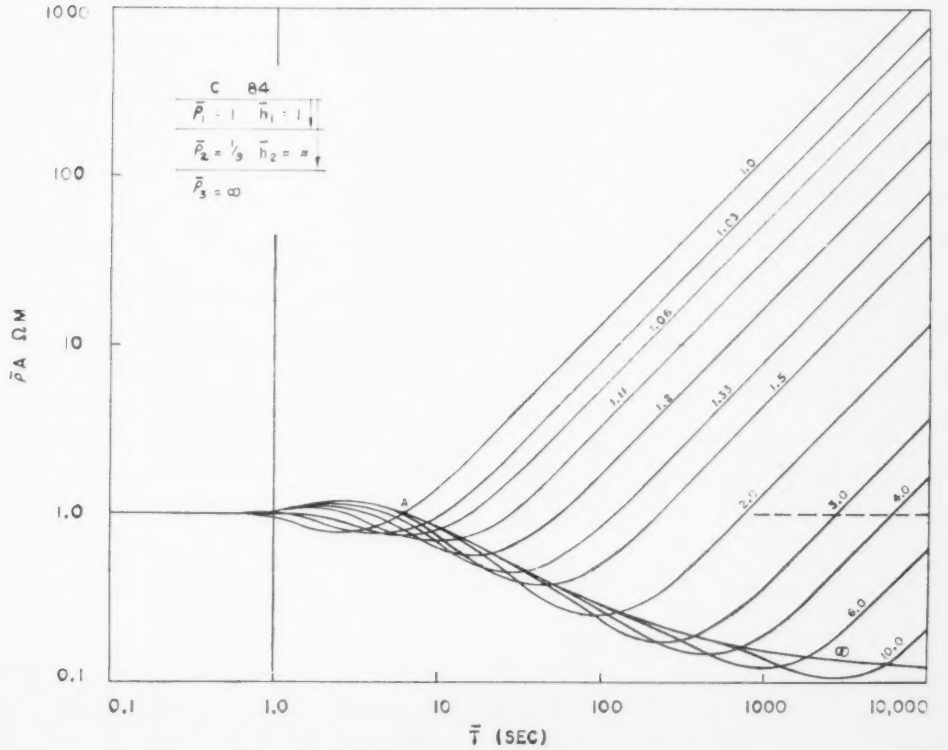
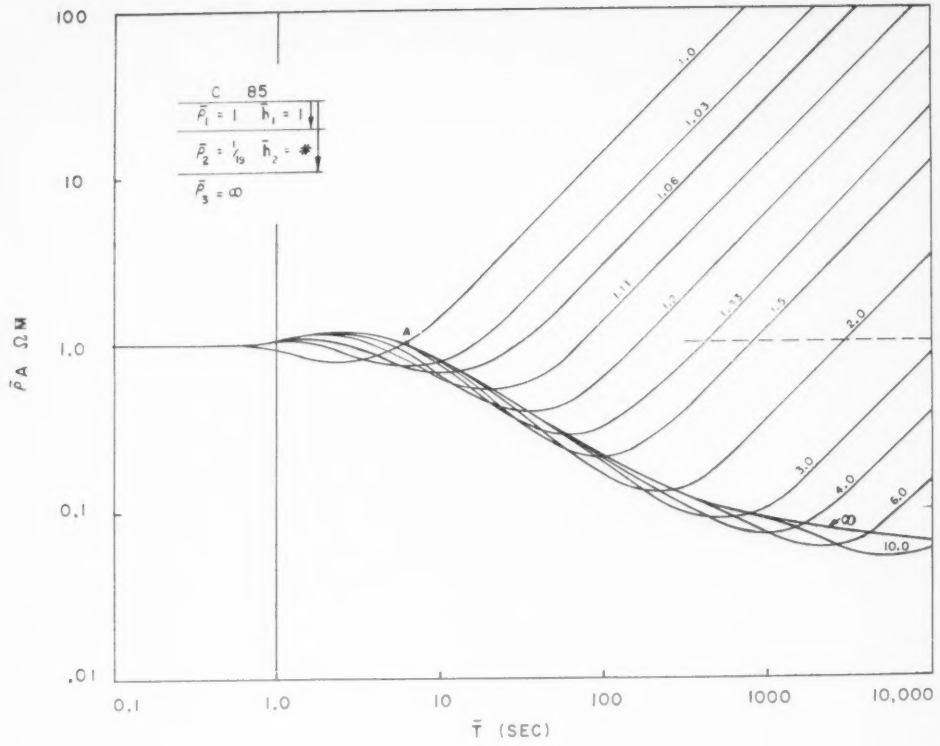


FIG. 5 (above) and 6 (below). Magneto-telluric, three-layer standard curves.

T (SEC)

FIG. 3 (above) and 4 (below). Magneto-telluric, three-layer standard curves.



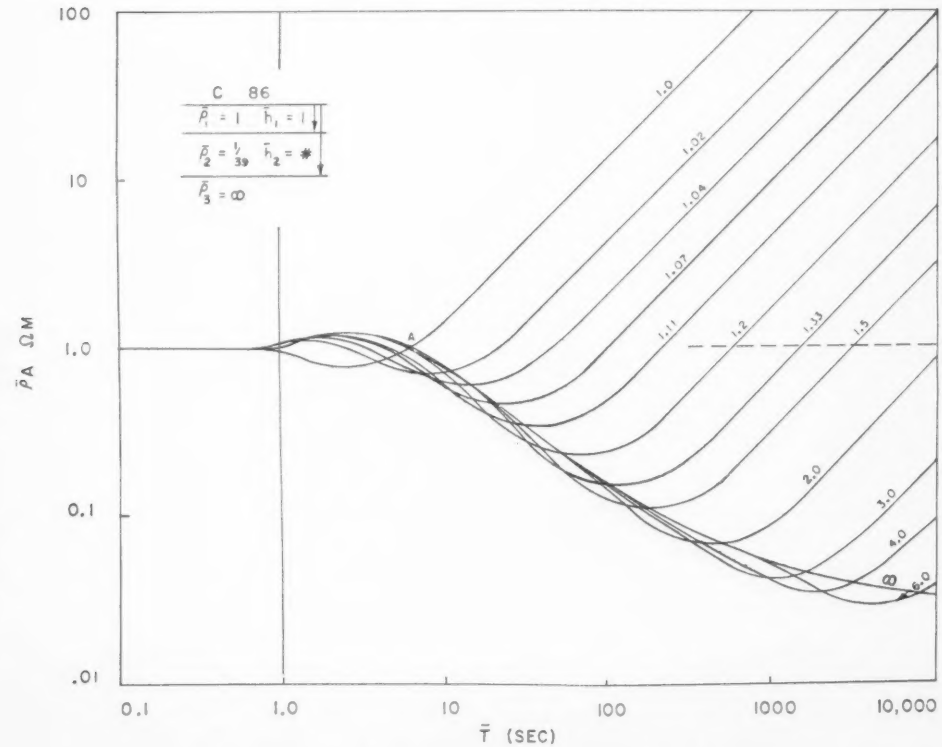
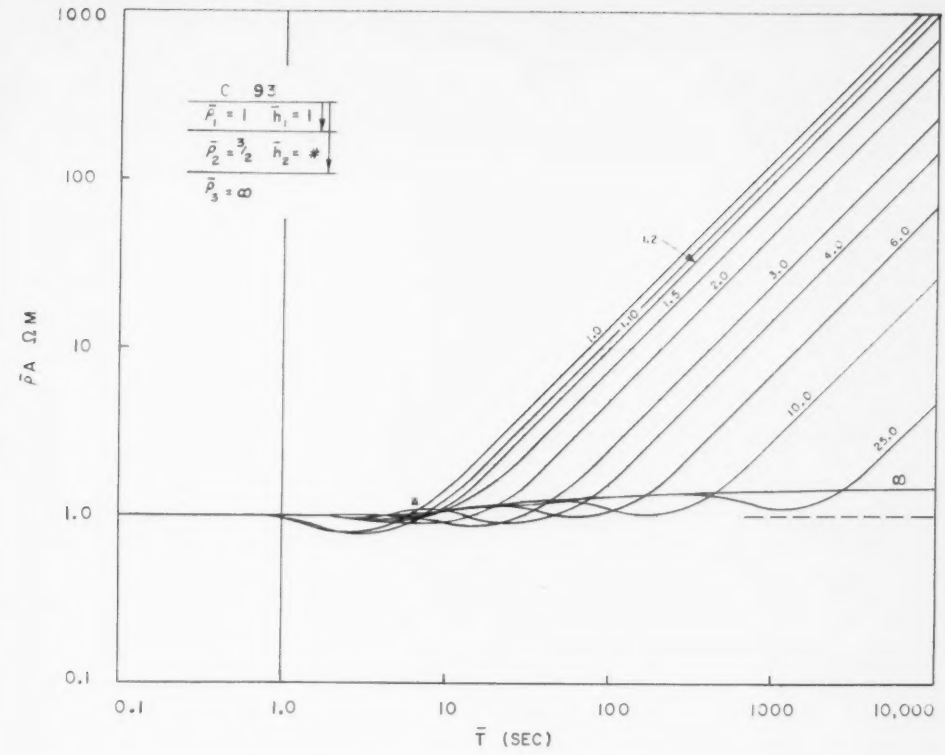


FIG. 7 (above) and 8 (below). Magneto-telluric, three-layer standard curves.

$\bar{T}$ (SEC)

FIG. 5 (above) and 6 (below). Magneto-telluric, three-layer standard curves.



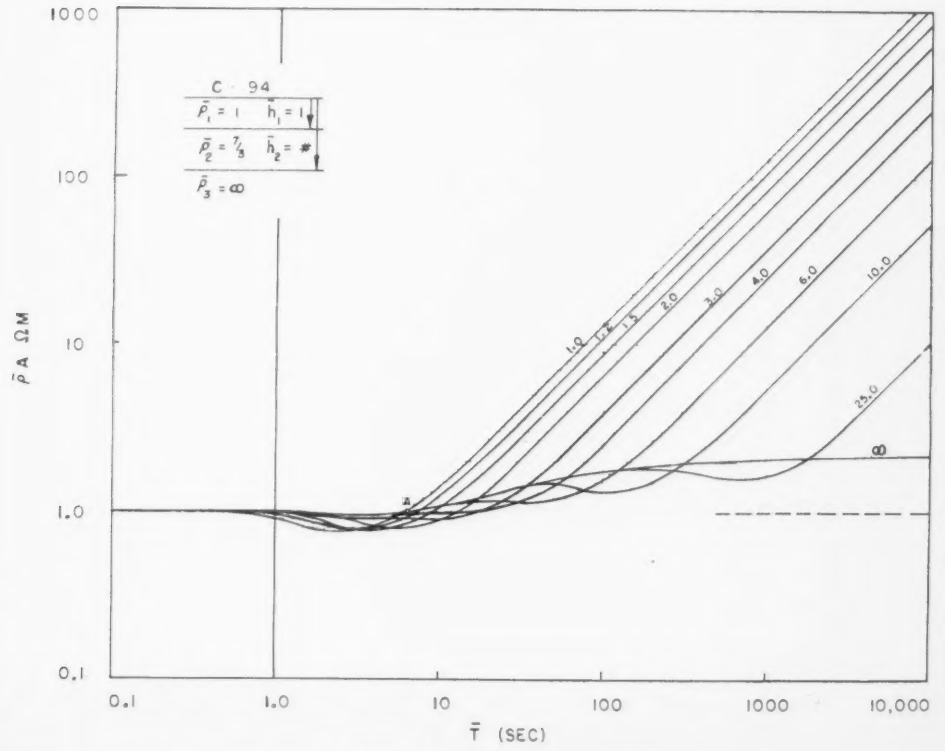
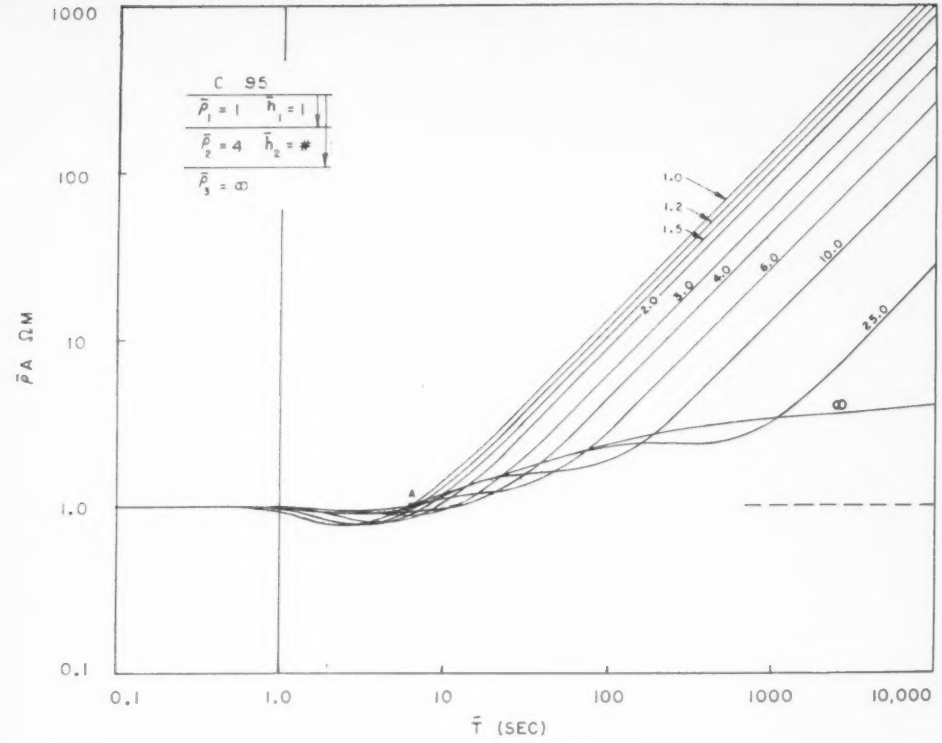


FIG. 9 (above) and 10 (below). Magneto-telluric, three-layer standard curves.

$\bar{T}$ (SEC)

FIG. 7 (above) and 8 (below). Magneto-telluric, three-layer standard curves.



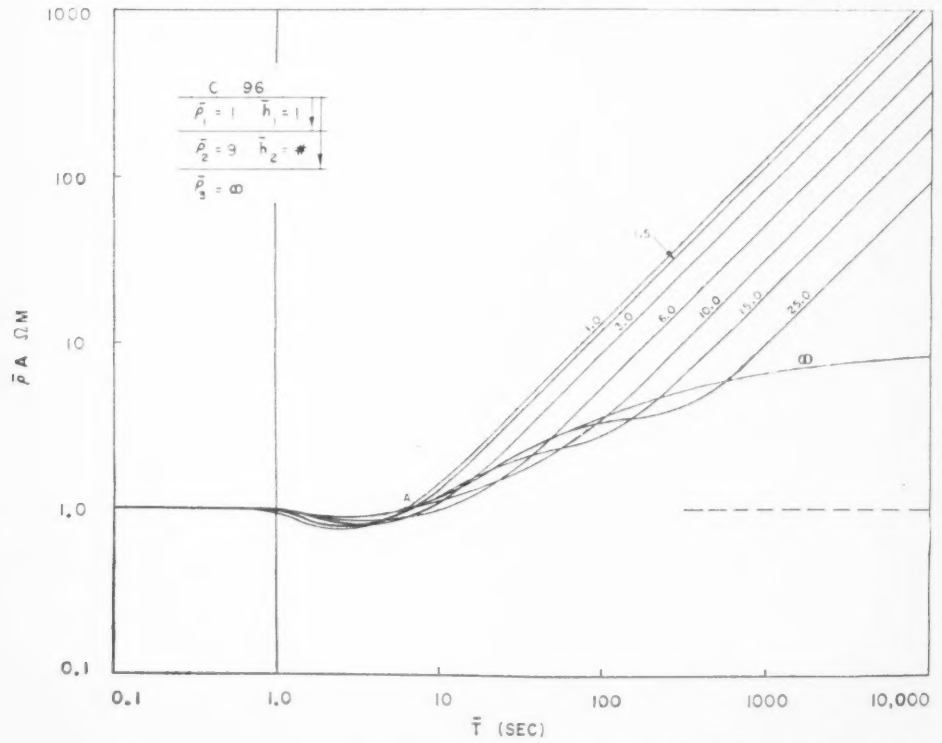


FIG. 11 (above) and 12 (below). Magneto-telluric, three-layer standard curves.

FIG. 9 (above) and 10 (below). Magneto-telluric, three-layer standard curves.

search Corporation who prepared the digital computer program and supervised the plotting.

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FIG. 11 (above) and 12 (below). Magneto-telluric, three-layer standard curves.

GEOPHYSICS, VOL. XXVI, NO. 4 (AUGUST, 1961), pp. 474-479, 4 FIGS.

AN INTEGRATION TECHNIQUE FOR AIRBORNE GRAVITY GRADIENT MEASUREMENTS*

NORMAN R. PATERSON†

Abstract: For some purposes it may be desirable to work with the gravity force g rather than its vertical gradient g'. A simple method has been tested by which measurements of g' on a plane surface can be integrated to produce values of g anywhere in space above the plane of measurement. The method appears to show promising results.

INTRODUCTION

It is well known that considerable attention is currently being paid to the measurement of gravity in airplanes. A method of obtaining the gravity force g has been described by Nettleton et al (1960). Experiments on airborne gravity gradiometry by Hunting Survey Corporation suggest that suitable instrumentation may be available within the next few years.

Studies have been made of the problems of data reduction and interpretation of gravity gradient data and also of the effects of topography on the measurements. Some of the results of these studies have been reported by Chinnery (1961).

An examination of the problem of integrating the gradient field was made by the writer as part of the above studies. The results have been helpful in comparing the sensitivity of a gradient measuring device with both standard and airborne gravimeters to masses of different shapes and depths. The results also suggest that where the gravity field is required for comparison or interpretation purposes, it can be obtained with sufficient accuracy by a simple integration technique. The technique described in this paper has been adapted from numerical procedures developed by Evjen (1936), Peters (1949), and others and uses identical processes of computation.

Throughout this paper the gradient of gravity is measured in units of milligals per foot. In the author's opinion this unit will be the most intelligible to those accustomed to working in gravity interpretation. For those that prefer the Eotvos unit E°, the conversion factor (1 mgal/ft = 3.28 $\times 10^4$ E°) is included where necessary.

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† Hunting Survey Corporation Limited, Toronto, Ontario.

MATHEMATICAL DEVELOPMENT

Let g represent the gravity force and g' be the vertical gradient of the force.

It is required to obtain g, knowing the value of g' on a surface of constant elevation above sea-level. Let $z=0$ on this surface and have a positive direction towards the center of the earth (see Figure 1). It is assumed that the gravity effects are due to a bounded distribution of masses lying below the plane $z=0$.

Let α, β be the co-ordinates of points in space in the x and y directions relative to the point of observation of the gradient g' as origin.

Following the method of Peters we write:

$$g'(x, y, z) = -\frac{z}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{g'(\alpha, \beta, 0)d\alpha d\beta}{\left[(x-\alpha)^2+(y-\beta)^2+z^2\right]^{3/2}}, \quad z \leq 0 \qquad (1)$$

Integrating with respect to z,

$$g(x, y, z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{g'(\alpha, \beta, 0)d\alpha d\beta}{\left[(x-\alpha)^2+(y-\beta)^2+z^2\right]^{1/2}} \qquad (2)$$

Since $g'(\alpha, \beta, 0)$ is not a known mathematical function, the integral must be evaluated numerically.

Let

$$\alpha - x = r\cos\theta \qquad \beta - y = r\sin\theta$$

and

$$\overline{g'(r)} = \frac{1}{2\pi}\int_0^{2\pi} g'(r, \theta)d\theta \qquad (3)$$

then

$$g(x, y, z) = \int_0^\infty \frac{\overline{g'(r)}dr}{(z^2 + r^2)^{1/2}}. \qquad (4)$$

Evaluating at $z = -h$ and replacing integrals by sums,

$$g(x, y, -h) = \frac{\overline{g'(0)} + \overline{g'(b_1)}}{2} \int_0^{b_1} \frac{rdr}{(h^2 + r^2)^{1/2}} + \frac{\overline{g'(b_1)} + \overline{g'(b_2)}}{2} \int_{b_1}^{b_2} \frac{rdr}{(h^2 + r^2)^{1/2}} + \cdots \text{etc.} \qquad (5)$$

Integrating,

$$g(x, y, -h) = -\frac{\overline{g'(0)}}{2}\left[(h^2 + b_1^2)^{1/2} - h\right] - \frac{\overline{g'(b_1)}}{2}\left[(h^2 + b_2^2)^{1/2} - h\right] - \cdots \text{etc.} \qquad (6)$$

This can be expressed in the form of the series

$$g(x, y, -h) = -\sum_0^\infty c_n g'(b_n) \qquad (7)$$

where

$$c_n = \tfrac{1}{2}\left[(h^2 + b_{n+1}^2)^{1/2} - (h^2 + b_{n-1}^2)^{1/2}\right]$$

and

$$b_0 = b_{-1} = 0 \qquad (8)$$

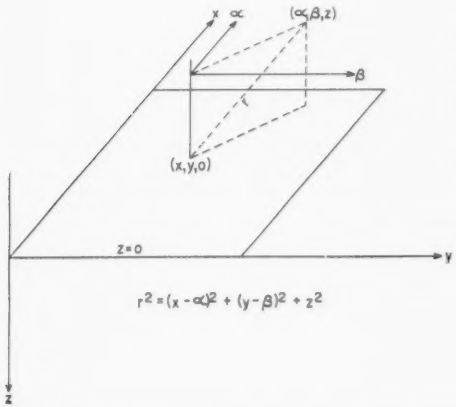


FIG. 1. Co-ordinate system.

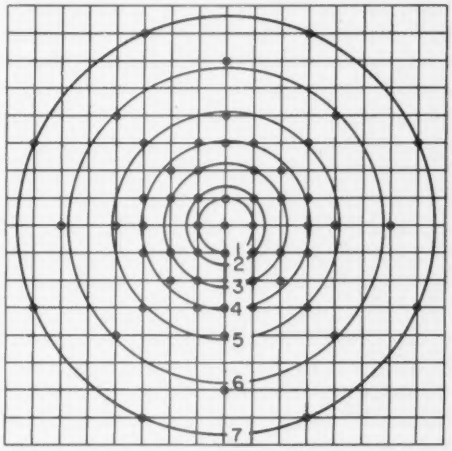


FIG. 2. Grid system showing circles of integration.

which at $h = 0$ reduces to:

$$c_n = \frac{b_{n+1} - b_{n-1}}{2}. \qquad (9)$$

Equations (7) and (8) can be used to obtain the gravity force g on the surface $z = -h$ from measurements of the gradient g' on the surface $z = 0$.

Equations (7) and (9) can be used to obtain g from measurements of g', both on the surface $z = 0$.

NUMERICAL EXAMPLES

Two examples have been chosen to test the applicability of the above method of integration to actual gravity data. Calculations of g are made on the surface $z = 0$ from values of g' which correspond to two simple models. These are compared with actual values of g which correspond to the models.

Radii are chosen according to the method of Peters (1949) with a slight modification of the fourth circle (b_4). The radii are expressed as multiples of the grid spacing S (see Figure 2).

Radii b_n	*Coefficients* c_n (×*Grid Spacing* S)
$b_0 = 0$	$c_0 = 0.500$
$b_1 = 1$	$c_1 = 0.707$
$b_2 = 2$	$c_2 = 0.618$
$b_3 = 5$	$c_3 = 0.812$
$b_4 = 9.23$	$c_4 = 0.943$
$b_5 = 17$	$c_5 = 1.396$
$b_6 = 34$	$c_6 = 1.746$
$b_7 = 58$	

For the purposes of the present test the series (7) has been cut off after the term $c_4\ g'(b_4)$ to simplify the calculations. The expression used is therefore:

$$g(x, y, 0) = -S[0.500g'(0)+0.707g'(1)+0.618g'(\sqrt{2}) +0.812g'(\sqrt{5})+0.943g'(\sqrt{9.23}). \quad (10)$$

It may be observed that this is not a convergent series unless g' converges. For even increments in the radii b_n the coefficients c_n will be constant. On a single anomaly g' must converge according to at least the second power of the radius. On multiple anomalies, however, the convergence is not so obvious and may rely mainly on the fact that at large radii the circles will pass through both positive and negative areas and sample increasingly diluted fields.

Example (1)

The fields g and g' of a single sphere have been plotted on a plane at height $h=2{,}000$ ft above center. The sphere has a radius $\rho=1{,}000$ ft and density contrast $\delta=1.0$ c.g.s. with respect to its surroundings. The grid spacing chosen is $S=1{,}000$ ft.

The expressions used in plotting the fields are:

$$g = \frac{4}{3}\pi\delta\rho^3 G\,\frac{h}{(x^2+h^2)^{3/2}} \quad (11)$$

$$g' = \frac{4}{3}\pi\delta\rho^3 G\left[\frac{1}{(x^2+h^2)^{3/2}}\right]\cdot\left[1-\frac{3h^2}{(x^2+h^2)}\right]. \quad (12)$$

The fields have been evaluated out to a distance of 7 grid units from the center. Beyond this distance they are assumed to be zero for the purposes of this test.

Values of g' derived from equation (12) were then used to obtain g through the expression (10) using an IBM "650" electronic computer. These have been plotted at the same scale as the maps of g and g' derived from equations (11) and (12). The three maps so obtained are reproduced in Figure 3.

The calculated g map (Figure 3(c)) conforms quite well in both shape and amplitude with the theoretical g map (Figure 3(a)). The small differences in amplitude near the central part of the main anomaly are caused by cutting off the expansion (7) after the first five terms. Inaccuracies near the periphery are caused by assuming zero values beyond the seventh grid interval in the theoretical model.

Example (2)

A complex model was built up from three spheres using the calculations of example (1). Composite maps of g and g' were obtained by summing three sets of values of g and g' derived for the three spheres using appropriate horizontal displacements. These maps are reproduced in Figures 4(a) and 4(b).

Calculations of g were then made using the expression (10) by means of an IBM "650" electronic computer (Figure 4(c)).

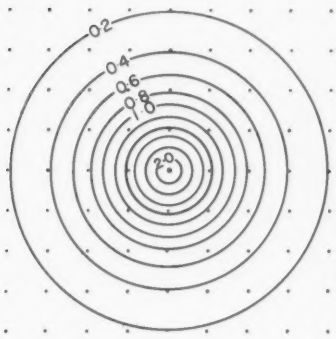
The map of calculated g differs more from the theoretical g map than was the case with the simple model. More amplitude difference and distortion occurs in the central part than was the case in example (1). This is because the anomaly is more spread out and requires a greater number of circles of integration. Near the periphery the discrepancy is more apparent and is brought about partly by the approximations made in constructing the g' map.

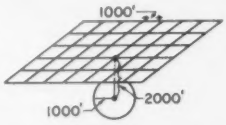
Despite these differences the two maps agree quite well in general form and amplitude. Even with the gross approximations made in this test, errors in g have been kept to roughly 10 percent of the maximum anomaly. It is considered that better results could be obtained by increasing the number of circles from four to seven.

CONCLUSIONS

If the vertical gravity gradient g' can be measured to an accuracy of 10^{-5} mgal/ft, it is possible to obtain maps similar to those of Figures 3(b) and 4(b) by airborne surveys. To achieve similar definition of the anomaly tested, the gravity force g must be measured to an accuracy of 10^{-2} milligals, possible on the ground but not by any known techniques in the air. The integrated equivalents of Figures 3(b) and 4(b), as illustrated by the maps of g in Figures 3(c) and 4(c), show errors of the order of 10^{-1} milligals. This is still well below the minimum change in g that is measurable by present airborne gravity techniques.

It is considered that integration methods, similar to the above but more carefully carried out,

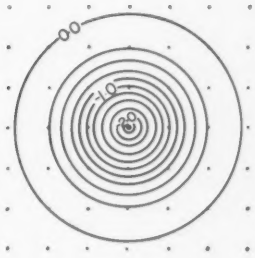


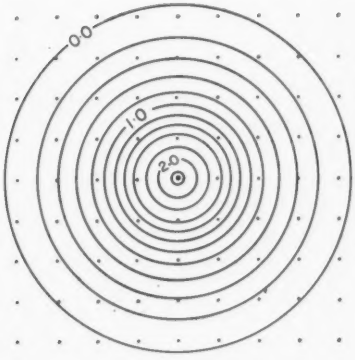


Grid Interval = radius = height = 1000 ft.
Density contrast = 1·00 c.g.s.

(a)
VERTICAL GRAVITY FORCE "g"
(milligals)
CONTOUR INTERVAL : 0·2 milligals

(b)
VERTICAL GRAVITY GRADIENT "g"
(units of 10^{-3} milligals / foot)
CONTOUR INTERVAL : 0·2 X 10^{-3} milligals/foot

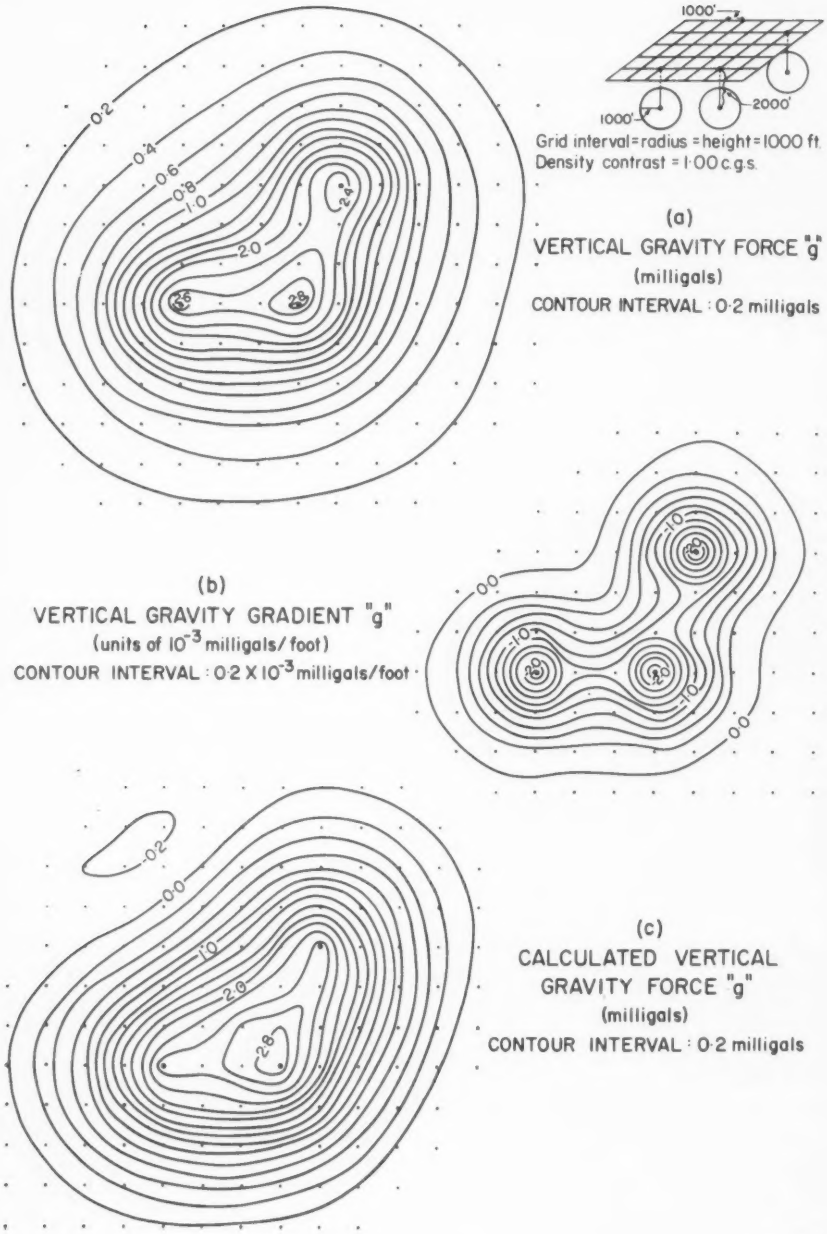




(c)
CALCULATED VERTICAL
GRAVITY FORCE "g"
(milligals)
CONTOUR INTERVAL : 0·2 milligals

NOTE: 1 milligal/foot = $3.28 \times 10^4 E^o$

FIG. 3



NOTE: 1 milligal/foot = $3.28 \times 10^{4} E^{\circ}$

FIG. 4

can achieve useful results in converting measurements of g' to more conventional and sometimes desirable values of g.

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GEOPHYSICS, VOL. XXVI, NO. 4 (AUGUST, 1961), PP. 480-489, 6 FIGS.

TERRAIN CORRECTIONS FOR AIRBORNE GRAVITY GRADIENT MEASUREMENTS*

M. A. CHINNERY†

Abstract: A method is given for the calculation of terrain corrections for airborne measurements of the vertical gradient of gravity. This includes a short account of the theory concerned, a description of the practical procedure, a complete set of numerical tables, and some examples of their application. The method described is shown to be very flexible, both with regard to aircraft height and to complexity of topography. Some discussion is also given of the magnitude of topographic effects on the gravity gradient, and it is shown that terrain corrections are in general more important here than in normal gravity work.

INTRODUCTION

The usefulness of the vertical gradient of gravity in the interpretation of gravity anomalies has been stressed by a number of writers. Of these, Evjen (1936) was probably the first, and in the last few years several papers on the subject have been published by Russian geophysicists (e.g. Klushin, 1957). The methods used are generally based on the derivation of the vertical gradient from normal gravity measurements (e.g. Raspopov, 1958), or even from second derivative data (Ackerman and Dix, 1955).

More recently, instruments are being developed that will permit direct measurement of the gravity gradient from the air. Within a few years it may be expected that airborne gradiometers will be available with sufficient accuracy (of the order of 10^{-5} mgal/ft) to make quantitative surveys possible. Although the data so obtained could be reduced to ordinary gravity by an integration technique, it is obviously desirable that both corrections and interpretations be based on the actual measurements. In particular, a method for calculating terrain corrections is necessary.

Raspopov (1959) has shown, using the gradients calculated from a ground g survey in the Caucasus, that the vertical gradient is strongly influenced by near surface features. In fact, as we shall show, the gradient produced at an aircraft by an average terrain is of the same order (between 10^{-3} and 10^{-4} mgal/ft) as that due to some common ore bodies. Terrain corrections will therefore be more important here than in the case of normal gravity.

The only reference to this subject in the literature to date is by Balavadze (1957), who has proposed, for ground gradient data, a method of terrain corrections completely analogous to that of Hammer (1939) for g. In this paper we shall show some basic difficulties in Balavadze's method, particularly for the airborne case, and suggest a more accurate means of eliminating terrain effects.

Unfortunately, airborne gradient data are not yet available with any reliability and therefore the examples worked here are theoretical ones. However, it will be shown that the method given has considerable flexibility and should be adaptable to any type of terrain likely to be found in practice.

Throughout this paper the gradient of gravity is measured in units of milligals per foot. In the author's opinion this unit will be the most intelligible to those accustomed to working in gravity interpretation. For those who prefer the Eotvos unit E°, the conversion factor ($1 \text{ mgal/ft} = 3.28 \times 10^4$ E°) is included where necessary.

THE MAGNITUDE OF TOPOGRAPHIC EFFECTS

Perhaps the most useful formula for calculating the magnitude of topographic effects is that giving

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† Hunting Survey Corporation Limited, Toronto, Ontario.

the gradient profile over a two-dimensional sloping contact (Figure 1). It can be shown that the vertical gradient of gravity at P is given by:

$$\frac{\partial g}{\partial z} = 2G\rho\left[\alpha\left(\tan^{-1}\frac{L}{z} - \tan^{-1}\frac{x}{d}\right) - \frac{\beta}{2}\ln\frac{(z^2+L^2)}{(x^2+d^2)}\right] \quad (1)$$

where

$$\alpha = \sin^2 i$$
$$\beta = \sin i \cos i$$
$$z = d + h$$
$$L = x + h\cot i.$$

Here i is the angle of the step, h its thickness, d the height of the measuring plane, and ρ is the density difference between the step and the surrounding material.

Using equation 1 as it stands we can calculate the profiles due to faults or cliffs, and by subtracting two formulae of this type we can determine the effects of dykes or anticlinal structures (depending on the values of i chosen). Also, the features can be either topographical or deep-seated, depending on d and ρ.

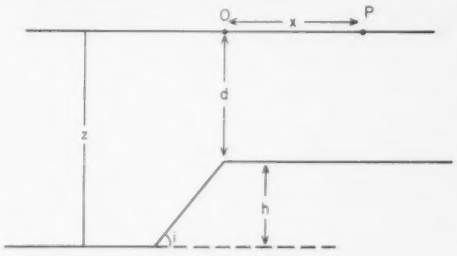

FIG. 1. Two-dimensional sloping contact.

As examples of this, Figure 2 shows the variation in the response with depth of a ridge of height 400 ft, and width 1,000 ft, as seen by an aircraft. The density contrast used is $\rho = 1.0$, and

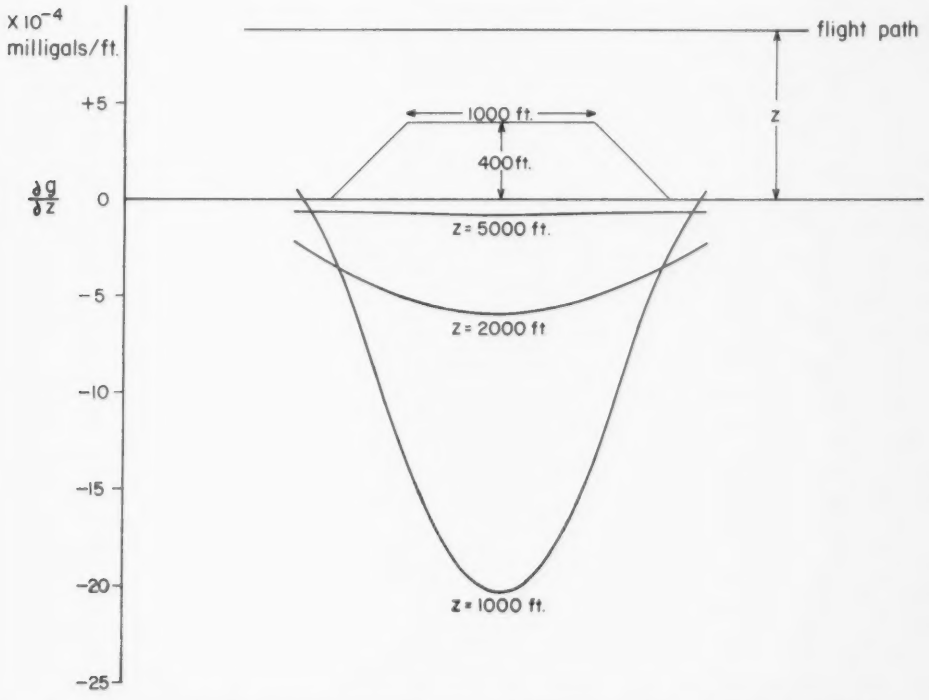

FIG. 2. Variation of gradient profile with depth over a two-dimensional ridge. (1 mgal/ft = 3.28×10^4 E°)

it must be noted that for a topographical feature ($\rho = 2.0$ at least) the response will be at least doubled. These values should be compared with those of, for example, a sphere of radius 1,000 ft, with top of sphere at 1,000 ft below the aircraft. The peak response of this will be 2.13×10^{-3} mgal/ft.

These calculations indicate clearly the importance of terrain effects. In general, vertical gradient data are much more sensitive to near surface masses than are normal gravity data, and terrain corrections will be necessary unless the ground surface is very flat. However, as we shall show later, these corrections can be calculated sufficiently accurate to make detailed surveys possible under most conditions.

BASIC FORMULAE

The methods described here are based on the same principle as the Hammer chart, in that the topographic relief around a station is divided into a series of concentric cylinders. Each cylinder is then divided into radial compartments such that the elevation of the ground within a compartment may be considered constant. Since we are interested in the airborne case, we have to remove the effects of topography down to some datum plane.

We consider first the gravity gradient due to a cylinder of height h and radii r_1 and r_2, resting on a datum plane, at a point P on the axis of the cylinder and height z above the datum (Figure 3). The origin of cylindrical coordinates (r, θ, z_0) is taken at the intersection of the axis of cylinder with the datum plane, and the z_0 axis points upwards.

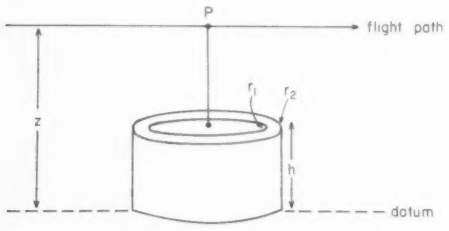

FIG. 3. To calculate the terrain correction at P the ground below the station is divided into a series of concentric cylinders. (A typical one of these is shown.) The combined effect at P of all such cylinders is given in equation 4.

The gravitational potential U at P is given by:

$$U = G\rho \int_0^h \int_0^{2\pi} \int_{r_1}^{r_2} \frac{r\,dr\,d\theta\,dz_0}{\sqrt{r^2 + (z - z_0)^2}}.$$

The vertical gradient of gravity at P is then:

$$\frac{\partial g}{\partial z} = -\frac{\partial^2 U}{\partial z^2} = -\frac{\partial^2 U}{\partial z_0^2}$$

i.e.

$$\frac{\partial g}{\partial z} = -G\rho \int_0^h \int_0^{2\pi} \int_{r_1}^{r_2} \frac{\partial^2}{\partial z_0^2}\left[\frac{1}{\sqrt{r^2 + (z - z_0)^2}}\right] r\,dr\,d\theta\,dz_0$$

$$= -G\rho \int_0^{2\pi} \int_{r_1}^{r_2} \left[\frac{(z - z_0)}{\{r^2 + (z - z_0)^2\}^{3/2}}\right]_{z_0=0}^{z_0=h} r\,dr\,d\theta. \qquad (2)$$

Now let

$$f(r, z) = \frac{z}{[r^2 + z^2]^{3/2}}.$$

Then

$$\int f(r, z)\,r\,dr = -\frac{z}{\sqrt{r^2 + z^2}} = -g(r, z), \text{ say.}$$

$$\therefore \frac{\partial g}{\partial z} = 2\pi G\rho \int_{r_1}^{r_2} [f(r, z) - f(r, z - h)]\,r\,dr$$

$$= 2\pi G\rho[g(r_1, z) - g(r_2, z) - g(r_1, z - h) + g(r_2, z - h)].$$

If there are n such cylinders, and the ith cylinder is divided into m compartments, the total effect at P due to terrain is given by:

$$\frac{\partial g}{\partial z} = \sum_{i=1}^{i=n} \frac{2\pi G\rho}{m} \sum_m [g(r_{i-1}, z) - g(r_i, z) - g(r_{i-1}, z - h_{mi}) + g(r_i, z - h_{mi})]. \qquad (3)$$

In principle, equation 3 above could be used to calculate terrain corrections. However, it will be shown in the next section that this process has

some grave disadvantages, particularly in the airborne case. A more useful formula is obtained as follows.

Let each cylinder be divided into the *same* number of compartments m, and consider the integration over all the terrain involved. In this case, equation 2 becomes:

$$\frac{\partial g}{\partial z} = -G\rho \int_0^{2\pi} \int_0^{\infty} [f(r, z) - f(r, z - h)] r dr d\theta$$

$$= \frac{2\pi G\rho}{m} \sum_m \left[1 - \int_0^{\infty} f(r, z - h_m) r dr \right].$$

If we now divide the integration into the radial zones with radii $0, r_1, r_2, \cdots, r_n, \infty$, then on performing the integrations we finally obtain:

$$\frac{\partial g}{\partial z} = \frac{2\pi G\rho}{m} \sum_m \left[\{ g(r_1, z - h_{m1}) - g(r_1, z - h_{m2}) \} \right.$$
$$\{ g(r_2, z - h_{m2}) - g(r_2, z - h_{m3}) \}$$
$$+ \cdots\cdots\cdots\cdots\cdots$$
$$\left. + \{ g(r_n, z - h_{mn}) - g(r_n, z - h_{m\infty}) \} \right] \quad (4)$$

where

$$g(r, z - h) = \frac{(z - h)}{\sqrt{r^2 + (z - h)^2}}.$$

BALAVADZE METHOD

Balavadze (1957) has proposed a method for the correction of ground gradient data. His formulae are approximations to equation 3 above, when z is set equal to zero.

The extension of this method for airborne work, using equation 3, is the obvious approach to terrain corrections. This would permit the construction of a chart like the Hammer chart with a suitable number of compartments in each radial zone so that each is approximately square. A table of $\partial g/\partial z$ against h for each zone could be calculated and used in the usual way. Each compartment in this case would have the property that $\partial g/\partial z = 0$ if $h = 0$.

However, a major difficulty arises when the datum plane does not coincide with the average elevation of an area, or part of an area, as may occur quite often. In this case, h may be quite large for each compartment. The importance of this fact is shown as follows.

Consider, for example, a perfectly flat region of elevation 300 ft above datum (height of aircraft = 1,000 ft above datum). Theory shows that an infinite flat sheet of uniform thickness produces a zero vertical gradient at any observation point P above it. However, the contributions from the individual zones for typical radii are given in Table 1 (here a typical density of $\rho = 2.0$ has been used).

Table I

r_{n-1}	r_n	$\frac{\partial g}{\partial z}$ (milligals per foot)
0	100′	-1.298×10^{-4}
100′	250′	-5.976×10^{-4}
250′	500′	-13.358×10^{-4}
500′	1,000′	-13.537×10^{-4}
1,000′	2,000′	$+4.292 \times 10^{-4}$
2,000′	5,000′	$+15.180 \times 10^{-4}$
5,000′	10,000′	$+7.108 \times 10^{-4}$
10,000′	20,000′	$+3.757 \times 10^{-4}$
20,000′	50,000′	$+2.292 \times 10^{-4}$
50,000′	∞	$+1.540 \times 10^{-4}$

Addition shows that the total effect at P is zero. But several of the contributions are very large, and subtracting large, almost equal, quantities will lead to enormous errors in practice. Moreover, using this technique, account must be taken of the terrain at large distances from the station. This is not only undesirable, but, as will be shown in the next section, is also unnecessary.

THE PROPOSED METHOD OF CORRECTIONS

An altogether more satisfactory approach to this problem is obtained by using equation 4. We can consider the quantities in the curly brackets of this expression to be the contributions to the gradient, and these have a number of important properties.

(1) They depend on the difference in height of two compartments adjacent to each radius. Hence, the contributions can be considered as arising at the radii.

(2) If this difference in height is zero at a radius, there is no contribution to the gradient. This immediately eliminates the main difficulty of Balavadze's method.

(3) If the height of the terrain is small compared to the radius of the zone, the net contribution will be very small. Hence the topography at large distances from the station may be neglected.

(4) Since only $(z\text{-}h)$ occurs in the formulae, any aircraft height z may be used if the eleva-

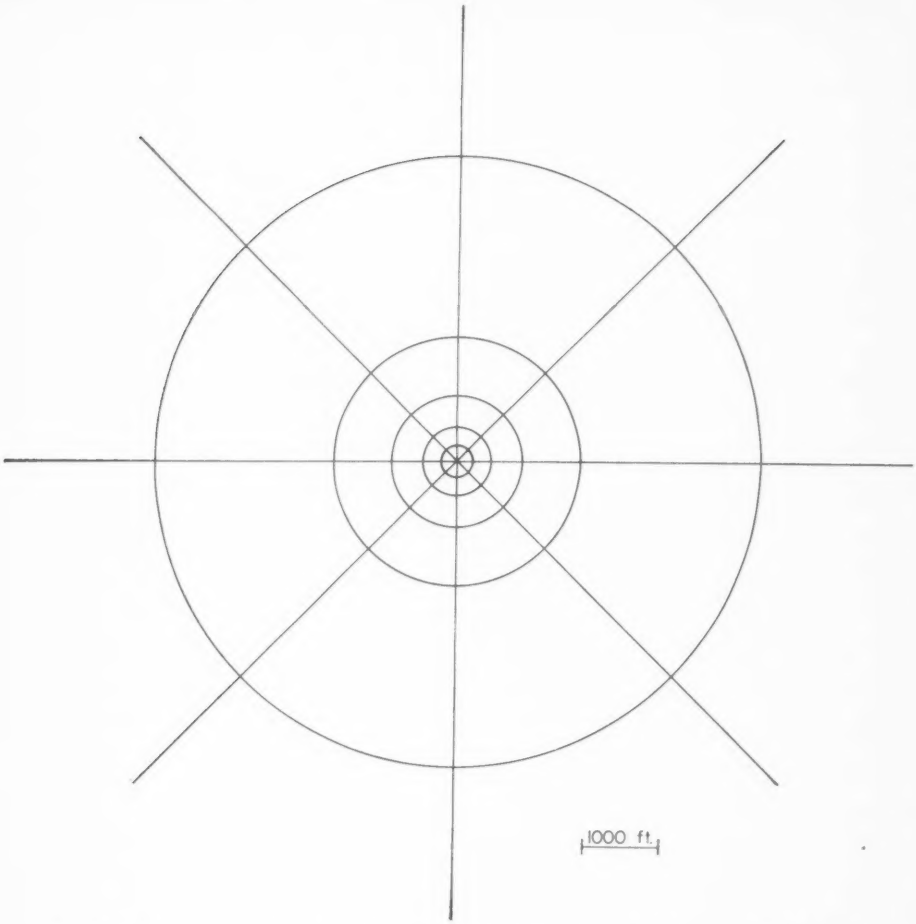

FIG. 4. Circular zone chart for eight radial compartments, and radii 250, 500, 1,000, 2,000, 5,000 ft.

tion datum is chosen accordingly. In the calculations that follow, z is chosen to be 1,000 ft, which may easily be the best height for surveys of this kind, but the same tables will apply for any z.

(5) Since the contributions arise at the radii; the number of radii may be changed to deal with particular types of topography, and the calculated tables will still apply. This is a notable feature of the method which has far more flexibility than the Hammer chart in normal gravity.

In order to apply this method, a basic set of radii is needed. It is suggested that the following be used: 250, 500, 1,000, 2,000, and 5,000 ft. More radii can be added later as necessary. Also, a basic number of radial divisions is required. This has been chosen to be 8, giving a total of 48 compartments, and 40 contributions to the gravity gradient. A chart constructed according to these specifications is shown in Figure 4. Note that the area between the outer radius and infinity must be counted as a compartment in order to obtain a contribution at $r=5{,}000$ ft. Such a chart should be drawn as an overlay for the topographical map of the area concerned, and the heights of the compartments averaged in the usual way.

We have now to evaluate the various terms of

Table II. Radius = 250 ft. 8 Compartments per Zone

h_2-h_1 \ h_1	−1,000	−900	−800	−700	−600	−500	−400	−300	−200	−100	0	100	200	300	400	500	600	700	800
−500						−9.4	−11.2	−13.6	−16.6	−20.6	−26.0	−33.4	−44.0	−59.5	−83.2	−120.9	−184.6	−297.6	−506.5
−400					−6.8	−8.1	−9.7	−11.7	−14.4	−18.0	−22.8	−29.5	−39.1	−53.3	−75.2	−110.4	−170.1	−277.2	−476.7
−300				−4.7	−5.5	−6.5	−7.9	−9.6	−11.8	−14.8	−19.0	−24.7	−33.0	−45.4	−64.6	−95.9	−149.8	−250.6	−430.9
−200			−2.9	−3.3	−4.0	−4.7	−5.7	−7.0	−8.7	−11.0	−14.1	−18.6	−25.0	−34.8	−50.2	−75.6	−119.9	−201.6	−356.7
−100		−1.3	−1.5	−1.8	−2.2	−2.6	−3.1	−3.9	−4.8	−6.1	−7.8	−10.6	−14.4	−20.3	−29.8	−45.8	−74.2	−127.1	−229.3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	1.3	1.5	1.8	2.2	2.6	3.1	3.9	4.8	6.1	7.8	10.6	14.4	20.3	29.8	45.8	74.2	127.1	229.3	
200	2.9	3.3	4.0	4.7	5.7	7.0	8.7	11.0	14.1	18.6	25.0	34.8	50.2	75.6	119.9	201.6	356.7		
300	4.7	5.5	6.5	7.9	9.6	11.8	14.8	19.0	24.7	33.0	45.4	64.6	95.9	149.8	250.6	430.9			
400	6.8	8.1	9.7	11.7	14.4	18.0	22.8	29.5	39.1	53.3	75.2	110.4	170.1	277.2	476.7				
500	9.4	11.2	13.6	16.6	20.6	26.0	33.4	44.0	59.5	83.2	120.9	184.6	297.6	506.5					

$\partial g/\partial z$ per compartment in units of 10^{-6} mgals/ft. h_1 and h_2 measured in feet. z = 1,000 ft. ρ = 1.0. h_1 is height of compartment nearest station.

Table III. Radius = 500 ft. 8 Compartments per Zone

h_2-h_1 \ h_1	−1,000	−900	−800	−700	−600	−500	−400	−300	−200	−100	0	100	200	300	400	500	600	700	800
−500						−34.3	−40.5	−48.2	−58.0	−70.5	−86.7	−108.0	−136.3	−174.7	−227.1	−299.3	−398.5	−532.8	−706.7
−400					−25.0	−29.4	−34.8	−41.6	−50.2	−61.2	−75.6	−94.5	−119.9	−154.4	−201.6	−266.9	−356.7	−478.1	−634.0
−300				−17.2	−20.1	−23.7	−28.2	−35.4	−40.9	−50.1	−62.2	−78.1	−99.6	−128.9	−169.2	−225.0	−302.0	−405.3	−536.3
−200			−10.6	−12.3	−14.4	−17.1	−20.4	−24.5	−29.8	−36.7	−45.8	−57.8	−74.2	−96.5	−127.4	−170.4	−229.3	−307.7	−404.7
−100		−4.9	−5.7	−6.6	−7.8	−9.3	−11.1	−13.4	−16.3	−20.3	−25.5	−32.4	−41.8	−54.7	−72.7	−97.7	−131.6	−176.1	−228.6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	4.9	5.7	6.6	7.8	9.3	11.1	13.4	16.3	20.3	25.5	32.4	41.8	54.7	72.7	97.7	131.6	176.1	228.6	
200	10.6	12.3	14.4	17.1	20.4	24.5	29.8	36.7	45.8	57.8	74.2	96.5	127.4	170.4	229.3	307.7	404.7		
300	17.2	20.1	23.7	28.2	35.4	40.9	50.1	62.2	78.1	99.6	128.9	169.2	225.0	302.0	405.3	536.3			
400	25.0	29.4	34.8	41.6	50.2	61.2	75.6	94.5	119.9	154.4	201.6	266.9	356.7	478.1	634.0				
500	34.3	40.5	48.2	58.0	70.5	86.7	108.0	136.3	174.7	227.1	299.3	398.5	532.8	706.7					

$\partial g/\partial z$ per compartment in units of 10^{-6} mgals/ft. h_1 and h_2 measured in feet. z = 1,000 ft. ρ = 1.0. h_1 is height of compartment nearest station.

Table IV. Radius = 1,000 ft. 8 Compartments per Zone

h_2-h_1 \ h_1	−1,000	−900	−800	−700	−600	−500	−400	−300	−200	−100	0	100	200	300	400	500	600	700	800
−500						−99.6	−113.7	−130.2	−149.7	−172.7	−199.7	−231.3	−268.3	−311.1	−359.9	−415.2	−475.4	−539.0	−602.9
−400					−74.2	−84.5	−96.5	−110.7	−127.4	−147.2	−170.3	−197.6	−229.3	−266.0	−307.7	−354.3	−404.7	−457.1	−508.6
−300				−51.9	−57.7	−67.3	−77.0	−88.5	−102.0	−117.9	−136.6	−158.6	−184.1	−213.5	−246.8	−283.5	−322.8	−362.9	−401.3
−200			−32.4	−35.9	−41.8	−47.7	−54.7	−63.0	−72.7	−84.2	−97.6	−113.4	−131.7	−152.6	−176.0	−201.7	−228.6	−255.4	−280.0
−100		−15.2	−17.2	−19.5	−22.3	−25.5	−29.3	−33.7	−39.0	−45.2	−52.5	−60.9	−70.7	−81.8	−94.2	−107.5	−121.1	−134.3	−145.7
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	15.2	17.2	19.5	22.3	25.5	29.3	33.7	39.0	45.2	52.5	60.9	70.7	81.8	94.2	107.5	121.1	134.3	145.7	
200	32.4	35.9	41.8	47.7	54.7	63.0	72.7	84.2	97.6	113.4	131.7	152.6	176.0	201.7	228.6	255.4	280.0		
300	51.9	57.7	67.3	77.0	88.5	102.0	117.9	136.6	158.6	184.1	213.5	246.8	283.5	322.8	362.9	401.3			
400	74.2	84.5	96.5	110.7	127.4	147.2	170.3	197.6	229.3	266.0	307.7	354.3	404.7	457.1	508.6				
500	99.6	113.7	130.2	149.7	172.7	199.7	231.3	268.3	311.1	359.9	415.2	475.4	539.0	602.9					

$\partial g/\partial z$ per compartment in units of 10^{-6} mgals/ft. h_1 and h_2 measured in feet. $z = 1{,}000$ ft. $\rho = 1.0$. h_1 is height of compartment nearest station.

Table V. Radius = 2,000 ft. 8 Compartments per Zone

h_2-h_1 \ h_1	−1,000	−900	−800	−700	−600	−500	−400	−300	−200	−100	0	100	200	300	400	500	600	700	800
−500						−171.1	−184.2	−198.1	−212.7	−228.1	−244.1	−260.6	−277.3	−294.2	−310.8	−327.0	−342.3	−356.3	−368.8
−400					−131.7	−141.8	−152.6	−164.0	−176.0	−188.6	−201.7	−215.1	−228.6	−242.1	−255.4	−268.1	−280.0	−290.8	−300.1
−300				−95.0	−102.3	−110.2	−118.5	−127.3	−136.6	−146.2	−156.2	−166.4	−176.6	−186.7	−196.5	−205.9	−214.4	−222.1	−228.5
−200			−60.9	−65.7	−70.7	−76.1	−81.8	−87.9	−94.2	−100.8	−107.5	−114.3	−121.1	−127.8	−134.3	−140.3	−145.7	−150.5	−154.3
−100		−29.3	−31.6	−34.1	−36.7	−39.5	−42.4	−45.5	−48.7	−52.0	−55.4	−58.9	−62.3	−65.6	−68.7	−71.6	−74.2	−76.3	−78.0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	29.3	31.6	34.1	36.7	39.5	42.4	45.5	48.7	52.0	55.4	58.9	62.3	65.6	68.7	71.6	74.2	76.3	78.0	
200	60.9	65.7	70.7	76.1	81.8	87.9	94.2	100.8	107.5	114.3	121.1	127.8	134.3	140.3	145.7	150.5	154.3		
300	95.0	102.3	110.2	118.5	127.3	136.6	146.2	156.2	166.4	176.6	186.7	196.5	205.9	214.4	222.1	228.5			
400	131.7	141.8	152.6	164.0	176.0	188.6	201.7	215.1	228.6	242.1	255.4	268.1	280.0	290.8	300.1				
500	171.1	184.2	198.1	212.7	228.1	244.1	260.6	277.3	294.2	310.8	327.0	342.3	356.3	368.8					

$\partial g/\partial z$ per compartment in units of 10^{-6} mgals/ft. h_1 and h_2 measured in feet. $z = 1{,}000$ ft. $\rho = 1.0$. h_1 is height of compartment nearest station.

Table VI. Radius = 5,000 ft. 8 Compartments per Zone

h_2-h_1 \ h_1	−1,000	−900	−800	−700	−600	−500	−400	−300	−200	−100	0	100	200	300	400	500	600	700	800
−500						−134.3	−136.7	−139.1	−141.4	−143.6	−145.7	−147.7	−149.6	−151.3	−152.9	−154.3	−155.6	−156.7	−157.6
−400					−106.4	−108.4	−110.4	−112.3	−114.1	−115.8	−117.4	−119.0	−120.4	−121.8	−123.0	−124.1	−125.0	−125.8	−126.5
−300				−79.1	−80.6	−82.1	−83.5	−84.9	−86.2	−87.5	−88.7	−89.8	−90.9	−91.8	−92.7	−93.4	−94.1	−94.7	−95.1
−200			−52.2	−53.2	−54.2	−55.2	−56.2	−57.1	−57.9	−58.7	−59.5	−60.2	−60.9	−61.5	−62.1	−62.5	−62.9	−63.3	−63.5
−100		−25.8	−26.4	−26.9	−27.4	−27.8	−28.3	−28.8	−29.2	−29.6	−30.0	−30.3	−30.6	−30.9	−31.2	−31.4	−31.6	−31.7	−31.8
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	25.8	26.4	26.9	27.4	27.8	28.3	28.8	29.2	29.6	30.0	30.3	30.6	30.9	31.2	31.4	31.6	31.7	31.8	
200	52.2	53.2	54.2	55.2	56.2	57.1	57.9	58.7	59.5	60.2	60.9	61.5	62.1	62.5	62.9	63.3	63.5		
300	79.1	80.6	82.1	83.5	84.9	86.2	87.5	88.7	89.8	90.9	91.8	92.7	93.4	94.1	94.7	95.1			
400	106.4	108.4	110.4	112.3	114.1	115.8	117.4	119.0	120.4	121.8	123.0	124.1	125.0	125.8	126.5				
500	134.3	137.7	139.1	141.4	143.6	145.7	147.7	149.6	151.3	152.9	154.3	155.6	156.7	157.6					

$\partial g/\partial z$ per compartment in units of 10^{-9} mgals/ft. h_1 and h_2 measured in feet. $s = 1{,}000$ ft. $\rho = 1.0$. h_1 is height of compartment nearest station.

equation 4. A set of tables has been constructed giving, for each radius, the contribution to the gradient for various h_1 and h_2. We use here h_1 and h_2 as the heights of the inner and outer compartments, respectively. These tables are given in Tables 2–6. It was found convenient to tabulate these values in terms of h_1 and (h_2-h_1). They may be used with advantage in this form, since an experienced operator will be able to judge the importance of a contribution easily from the difference in heights.

It will be found that a skilled operator, using mental interpolation, can obtain sufficient accuracy with the tables as they stand for most purposes. However, for unskilled operators, or for accurate work, it is suggested that each of the tables be plotted in graphical form on a large scale and used in this form.

If it is found necessary to extend the number of radii for any reason, new tables can be calculated using the following formula:

$$\frac{\partial g}{\partial z} = \frac{1.278 \times 10^{-2}}{m} \rho \left[\frac{(z-h_1)}{\sqrt{r^2+(z-h_1)^2}} - \frac{(z-h_2)}{\sqrt{r^2+(z-h_2)^2}} \right] \text{mgals/foot.} \quad (5)$$

If the number of radial divisions m is to be changed, each contribution must be multiplied by a numerical factor. The most convenient way of accomplishing this is to change the scale of the graphs mentioned above. It is suggested that, when these are constructed, two scales for the gradient be provided, corresponding to $m=8$, and $m=12$. These will cover all situations likely to be found in practice.

The density ρ, which occurs in these formulae, has the same significance as it does in the correction of normal gravity data. Thus, it must be adjusted until the topographic effects in the observed profiles are reduced to a minimum.

EXAMPLES OF THE USE OF THE METHOD

Since reliable airborne gradient measurements are not yet available, it has not been possible to check this method in any practical case. However, it has been used to determine the profile over a number of bodies whose theoretical profiles are known. Two examples of this are shown in Figures 5 and 6. Here we show examples of the ridge mentioned in section 1; the theoretical curves were obtained using equation 1.

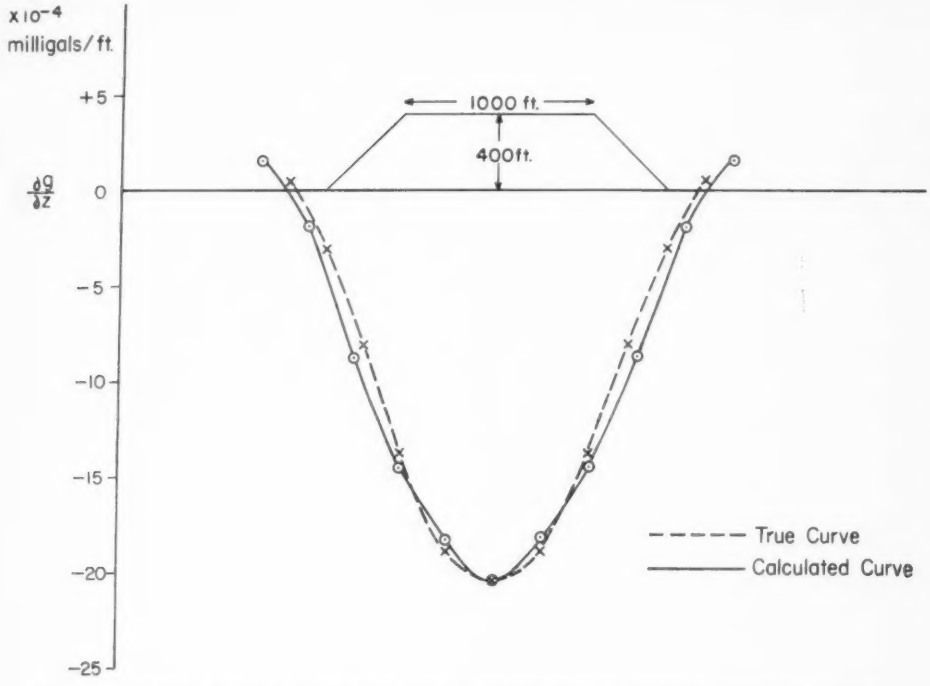

FIG. 5. Comparison between true profile and profile calculated using the suggested method for a typical two-dimensional ridge. (1 mgal/ft = 3.28×10^4 E.°)

Both of these applications were calculated by an unskilled operator (the author), at first attempt, and using mental interpolation of the tables given above. It should be pointed out that the cases chosen are two-dimensional, and therefore more likely to be influenced by truncation errors (due to stopping the integration at 5,000 ft) than most features to be found in practice. However, the accuracy obtained would be entirely adequate for most surveys, and more experience in averaging elevations would presumably produce even better results.

Some final points with regard to this method are:

(1) For the accuracy of the curves shown in Figures 5 and 6, it is sufficient to estimate elevations to the nearest 25 ft and to mentally interpolate in the tables given here;
(2) The time for a correction to be calculated is about 15–20 minutes per station for an unskilled operator, and this should be reduced to an average of about 10 minutes per station for an experienced person.
(3) It is suggested that a desk calculator be used to sum the contributions from the tables; and
(4) The contributions from the inside radius (250 ft) are small and in many cases may be neglected altogether. The contributions at the outside radius (5,000 ft) are very insensitive to absolute height h_1.

TERRAIN CORRECTIONS USING AN ELECTRONIC COMPUTER

Since a large number of stations may be covered in a short time using airborne instruments, it would be desirable that the gradient data so obtained be corrected by some automatic process such as an electronic computer. The technique described above is not very suitable for this kind of application since it would be difficult to average elevations automatically over a radial compartment.

A far better system in this case is one based on

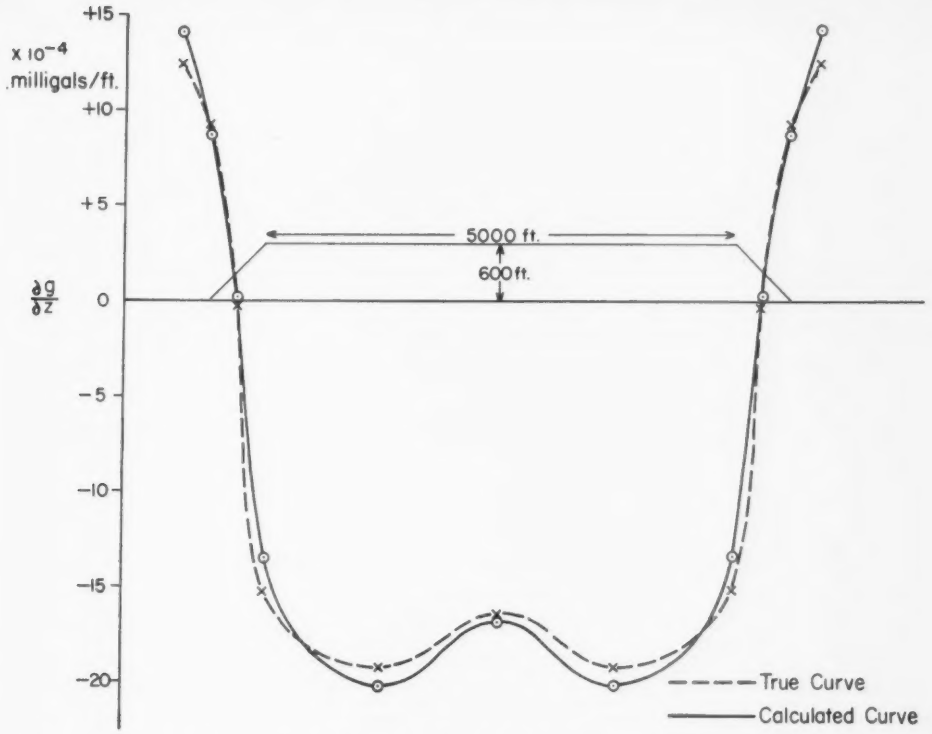

FIG. 6. Comparison between true profile and profile calculated using the suggested method for a typical two-dimensional ridge. (1 mgal/ft = 3.28×10^4 E°)

a rectangular or square grid, and the theoretical basis of such a system has been worked out by the author. However, there is little point in using this method if the time necessary to punch these values on cards and insert them into a computer program will probably be longer than the time needed to use a set of tables and complete the calculation by hand. The chief use of this technique will be on the development (which is in progress) of a device that will measure elevations directly from the aircraft or from photographs obtained in flight, recording them in a form suitable for direct insertion into a computer. The details of the method will depend largely on the design of this instrument and are left for a future paper.

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XXVI, NO. 4 (AUGUST, 1961), PP. 490–498, 4 FIGS.

REVIEW ARTICLE

GRAVITY SURVEYS IN HEAVY SAND DUNES*

G. C. COLLEY†

Abstract: The paper discusses the problems involved in desert surveys under the headings of "Access" and "Correction of Gravity Data." The types of sand formation are described. In planning a survey the importance of reconnaissance, aerial photographs, and the provision of suitable equipment are stressed. The advantages and disadvantages of motor transport, light aircraft, helicopters, and the operational procedures used with each are discussed. Terrain corrections are necessary on most stations and suggestions are given for their determination. The different densities of the dune sand and the "floor" introduce a problem in the determination of the Bouguer Correction. A method is given whereby close estimates of the sand thickness can be found by contouring on the "floor" or on minimum elevations. The resulting Bouguer values after computation are as regular as those found in areas of small elevational changes.

The expansion of exploration for oil in recent years, inevitably, has caused geophysical crews to push deeper and deeper into terrain that was once thought to be unworkable. Perhaps this has been most marked by surveys of the heavy sand deserts of North Africa and the Middle East—the Sahara and the Rub' al Khali (the Empty Quarter). The writer's experience has been with the latter area, but much of this paper is applicable to any areas of sand where dunes are common. The problem of conducting gravity surveys in these territories resolves into two main headings: 1. Access 2. Correction of data.

ACCESS

Sand patterns are quite variable, ranging from gently rolling sand dunes, with but a few feet from crest to trough, to sand "mountains" of enormous height. The usual form of dune is the so-called "crescent," the steep face is crescent-shaped and the other (the windward face) has more gentle slopes. The angle of rest of sand is about 30 degrees in theory. Experience suggests that sometimes this can be exceeded, possibly dependent on humidity and grain shape, although this appearance of a higher angle of rest may be largely illusionary. These crescent dunes range in height from a few feet to an estimated 300 ft, and no four-wheeled vehicle can climb the steep face. Often crescent dunes can pile up on top of each other in steps to comprise a sand "mountain" with an elevation above the "floor" of up to 700 ft. Sometimes they run in elongated ridges separated by smooth stretches of the "floor," usually a powdery gravel but occasionally salt flats or "sabkha" as they are known locally. Such an exposed area of the under-surface (termed a "shaq") may extend unbroken for a considerable distance, sometimes as long as 50 kms. This is a great help for vehicles travelling in that direction, but problems arise when travel is necessary at right angles to the ridges. As long as the direction of travel always takes the vehicle down the steep faces of the dunes, progress, if slow, is possible although there is always a danger of the vehicle rolling down if it slides around at right angles to the direction of travel. The really difficult and sometimes impossible direction is that towards the prevailing wind for this takes the vehicle up the steep faces of the dunes. However, usually it is possible to get over the shoulders of the dunes where the crescent form disappears, although even here gradients can often be too steep for the vehicle to climb. If the dunes are small, the car can be winched over.

In undertaking a geophysical survey of such territory, initial planning can determine the success or failure of such an operation. A knowledge of an area of sand elsewhere is not necessarily sufficient experience to attempt the surveys of new

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† Iraq Petroleum Company, Limited, London, England.

FIG. 1. Typical dune complex—South-East Arabia.

areas without a prerequisite of planning. Many of the remarks made in the following pages apply equally to gravity and seismic surveys and can be covered by four main subheadings.

(1) *Reconnaissance*

Perhaps one of the most important aids prior to the commencement of a survey is the provision of aerial photographs of the area. If these are not available, they can be substituted only by general reconnaissance forays into the sands in order to subdivide the area in general terms into light sand, heavy dunes, sand mountains, etc., so that the relative difficulty of access of each section can be appraised. Aerial reconnaissance must be supplemented by, at least, a limited amount of reconnaissance by car. Grain size and texture of the sand vary and can never be determined from aerial photographs alone.

With the photographic and reconnaissance information at hand it is possible to determine:

(a) the general trend of the country so that the direction of the profiles can be determined, fully utilizing the best routes;

(b) a division of the terrain into areas impassable to heavy transport and those areas to which supplies can be brought, to determine the siting of camps.

Once the division into heavy, medium, and light sand has been obtained; a coverage diagram must be drawn showing the approximate areas to be surveyed from each camp. Heavy sand areas, of course, are to have smaller area than those where the going is relatively easy.

In arriving at an order of survey of these areas, the season of the year is the controlling factor. In winter, when the sand is cold or after rainstorms, the sand compacts to form a crust, and it is relatively easy to get light transport over almost any terrain where the slopes are not too great. On the other hand, in the summer months, such areas can be surveyed only by constant winching and digging out, representing a great waste of time and money. Camps should be ar-

ranged so as to survey areas of light going in summer, medium going in autumn, medium/heavy in spring, and heavy in winter.

(2) *Camp Equipment*

The equipment chosen for use on a desert survey will depend entirely on the duration of the survey and the severity of the terrain to be traversed.

For a survey in the winter months only, there is no point in carrying large quantities of refrigeration equipment and air conditioners. On the other hand, if the survey lasts several years, including the summer months, the fatigue factor on the personnel must be taken into consideration. In the summer months in the sand deserts of the Middle East, shade temperatures can range up to 130°F. by day, rarely dropping much below 90°F. at night, as dunes radiate stored heat during the night. The writer would always recommend that air conditioned sleeping quarters be used in these conditions. For surveys of some duration, personnel prefer individual sleeping quarters rather than communal ones although this tends to increase the weight of equipment. Experience suggests that the effective increase in output per man more than justifies the additional expenditure.

If there is likely to be difficulty in getting heavy transport to the chosen camp sites, it is important that equipment should be lightweight and kept to a minimum, as should the number of personnel. In fact, if there is no problem in getting field data back to base, there is something to be said for keeping field men only in forward camps, party chiefs and computers remaining at the base, except for supervisory visits, although this is not entirely satisfactory.

(3) *Transport*

(a) Motor Vehicles

Choice of units varies with individual selection except that a broad classification into field vehicles and load carriers can be made. Personal preference inclines towards the $\frac{1}{2}$-ton pickup for field use, a few 1-ton pickups as load carriers in difficult territory, and either 3- or 5-ton load carriers for camp moves.

A characteristic of all vehicles should be that they are fitted with high and low ratio auxiliary gear boxes with a relatively easy system of transfer within the cab and with four-wheel drive available, preferably in all ratios.

The choice of tires varies for the field vehicles. Some prefer oversized tires with little or no tread to increase the flotation area; and others, special sand tires. These latter should have circumferential ribs as cross-treads tend to break the sand "crust." Usually tires are inflated at pressures considerably below those recommended by the manufacturers as a means of increasing the flotation area.

A percentage of load carriers and the heavier pickups should have winches fitted to assist in "rescue" operations.

It is considered that not less than 50 percent reserve vehicles should be carried to allow for adequate maintenance or vehicles stuck in the sand, so that the survey is not held up for lack of transport.

(b) Light Airplanes

If suitable landing strips are available near camp sites, there is a lot to be said for dispensing entirely with the heavy motor transport and using light airplanes for bringing up supplies and for camp moves. Such planes should be capable of taking off and landing within 300 yards with a reasonable payload of, say, $1\frac{1}{2}$ tons to bring up supplies of food, fuel, and water with the minimum of effort. The supply of water is the biggest problem as this can amount to six gallons per man per day in the hot summer months. Without careful control this figure can easily reach 10 gallons. One aircraft is fully utilized in the maintenance of one field party. These aircraft should always have two engines and be capable of maintaining height on one engine on full load as emergency landing grounds are few and far between in this terrain.

The wear and tear on airplanes is much less than on vehicles and the saving on maintenance staff, drivers, and supplementary personnel makes the use of air-supply economical.

(c) Helicopters

Experiments have been made in the use of helicopters both as substitutes for the field cars and for the load carriers. In both cases modification to normal routines are necessary. The small pay load makes helicopters prohibitive as load carriers for the supply of a normal camp. However, where small "fly" camps of a few men need supplies in territory impassable to heavy transport, they can be of considerable value.

Using helicopters as the sole means of transport for reading gravity stations in very heavy sand is

a slow and expensive operation. In the first place with an endurance of about four hours, allowing a safety margin and up to an hour for transit to and from the refuelling point (presumably main camp), there remains only about two hours available for survey time. It is doubtful, therefore, whether more than four hours effective work can be achieved daily. The constant change of temperature and pressure from ground level to flying height and back again is a little hard on all gravity meters which are not thermostatically controlled. Lastly, there is a considerable pickup of sand when the aircraft is on the ground and this causes abrasion of the rotor blades and clogging of filters. Maintenance schedules demand frequent inspections, and an average of about two days in seven are lost for this reason.

However, in areas of very heavy sand which can be surveyed by pickups in winter, helicopters can be very useful. In such areas vehicles can be left out at night together with the survey equipment. Helicopters are then used to ferry personnel and supplies to the car assembly point. Apart from the half hour, say, of flying time each way, a large proportion of the working day is spent on survey, and the flying time of the helicopters is considerably reduced. It is necessary, of course, that surveyors and gravity meter operators should survey the same stations on the same day, but this is necessary in any case as station markers soon disappear if there is any breeze present.

Helicopter pilots have found two further problems in flying over dune country. It is often difficult to judge the slope of a dune when landing, and navigation is not easy in this monotonous terrain. Slight drift of the aircraft due to winds can put the helicopter some hundreds of yards out at a rendezvous at a corner station marker which is very difficult indeed to identify from the air. This problem was solved by setting up overnight mobile beacons fitted with time switches at the required take off point. Homing on these beacons was a relatively simple matter. Painting of the car cabs with orange luminescent paint also improves air recognition.

(4) *Operational Procedures*

It has been mentioned already that station markings and car tracks disappear in very short time, but that this can be overcome by the gravity meter operator following closely behind the surveyors. Loop corner stations, however, are tied into on more than one occasion often several days apart and it is necessary that they should be well marked. Concrete blocks, empty oil drums, or petrol tins are some of the items used for marking, but even these will become covered in time.

As the large Middle East deserts lie within the tropics, the summer temperatures give rise to heat shimmer so that little or no surveying can be carried out after about 10 a.m. The rapid rise of temperature from night to day also has the effect of making the sand surface more powdery, and vehicles tend to stick in the sand much more easily after midmorning. Thus, both the surveying and meter reading are best completed before 10 a.m., so crews usually begin work at dawn.

In heavy sand there are unlikely to be landing strips for light aircraft, and heavy transport cannot move to bring up camp equipment. Thus, as no normal camps can be pitched, the problem arises of surveying areas many miles from camp over terrain where even light pickups may take several hours to traverse 10 miles. The time of travel from the nearest camp site to the working point and return at night becomes prohibitive. If helicopters are not available, a method has to be evolved to carry out the survey. In these circumstances the so-called "fly" camp has proved invaluable. Field men, only, set off with a few helpers to the work point accompanied by 1-ton pickups, sufficient to carry a small quantity of supplies and essential camp equipment. Even tents are usually dispensed with on these operations. Camp then moves with the work, which is comparatively easy as supplies are retained on the pickups and little or no camp equipment is required to be off-loaded. There is, of course, a limit to the length of time such camps can run. The lack of amenities and constant moves, often in considerable heat, are wearing on personnel. On the whole it is best to run "fly" camps for about a week or so at a time, giving the men breaks of a few days back in the main camp. Morale, and therefore output, can then be maintained for long periods.

It is important to set up an efficient rescue service under the control of the Party Chief. Field men are often stranded out at night when cars break down and accidents to cars and aircraft have been known, sometimes involving injury to personnel. It is essential that areas of work and the flight plans of aircraft should be agreed with the Party Chief before each sortie so that quick rescue can be effected. Radio links to base areas should be maintained on a watch system so that

aircraft can be called for in an emergency to fly out accident cases or provide early medical attention.

CORRECTION OF GRAVITY DATA

Two factors must receive prior consideration under this heading; first, the effect of the variations of topography on the gravity values and, second, the effect of the different material comprising the dunes and their "floor."

(1) *Terrain Corrections*

Since successive gravity stations along a line may, in areas of heavy sand, have elevations differing by as much as 100 meters; it is obvious that terrain corrections must be applied. It has been found that to arrive at a "smooth" gravity picture, terrain corrections are necessary at most stations. No reliable maps of these desert areas exist, and certainly there is little point in making them. The constant movement of the sand would render those maps quite unreliable some years later. Thus, the determination of the correction in the outer zones of a terrain correction chart becomes a problem. As a "better than nothing" method, a map can be drawn contoured on the elevations of the gravity stations (see Figure 2). Although not accurate, the general trends of the sand ridges can be interpolated from profile line to profile line across the loops, and a reasonable approximation to the truth is obtained. This map can be used to determine the outer zone corrections. The surveyors can make estimates of elevational changes within the inner zones in the field. This visual method is usually restricted by the undulating terrain to a range up to Zone D (170 meters outer limit) of Sigmund Hammer's chart (GEOPHYSICS, v. 4, 1939). The density to be used for these terrain corrections is that of the dune sand.

(2) *Sand (E.C.F.) Correctons*

It is obvious that the density of dune sand will differ considerably from that of the material comprising the "floor" of the dunes. Elevation correction factors (E.C.F.'s) of dune sand have been determined at 0.235 to 0.24 mg/m (densities 1.76 to 1.64 gm/cm^3). In the Arabian deserts the "floor" is often limestone with E.C.F.'s around 0.215 mg/m, sometimes much lower.

Clearly, there exists a necessity for raising the datum, but an arbitrary datum can introduce errors. The ideal datum would be the "floor" itself if the elevational contours on this surface could be determined. It is fortunate indeed that in the Middle East deserts wind erosion has reduced the "floor" to a relatively smooth surface which in places is almost an inclined plane. Very few irregularities exist on this surface and where present are rarely, if ever, sharp. This fact has been utilized to adjust the gravity values to allow for the low density dune sand. The elevation corrections at all stations are first computed using the true elevations of the stations and the E.C.F. applicable to the "floor." Stations on dune sand will always have too low a correction if the E.C.F. of the "floor" alone is used. "Windows" often reveal the underlying "floor" and field men are instructed to record the gravity stations which are sited on the "floor." Contour maps are then drawn on these spot heights. On the same map the difference of elevation to the nearest meter between the elevation of the "floor," as read from the contours, and the true elevation at each gravity station are recorded. These values give reasonably accurate figures for the sand thickness. Multiplying this sand thickness at each station by the difference in E.C.F.'s applicable to the "floor" and to the dune sand and adding this to the elevation correction previously determined will give the true Bouguer Correction. The resultant Bouguer Anomaly Map will be found to have values as regular as those recorded in territories with less irregular terrain.

The map showing the contours of the "floor" together with the sand thicknesses, often with the corrections added, has become known as the Sand Correction Map. Such a map for the same area as shown in Figure 2 can be seen in Figure 3. The figures above each station show true elevation (below) and sand thickness (above) with the gravity correction in brackets. The station elevations which were used for control of the contours are underlined. The resulting Bouguer Map is shown in Figure 4.

If no "windows" in the sand exposing the "floor" can be found, an approximate result can be obtained by contouring on "minimum elevations." These minimum elevations refer to the "valleys" between the sand ridges. Although this method will not give the exact Bouguer Anomaly, the error representing the departure of the as-

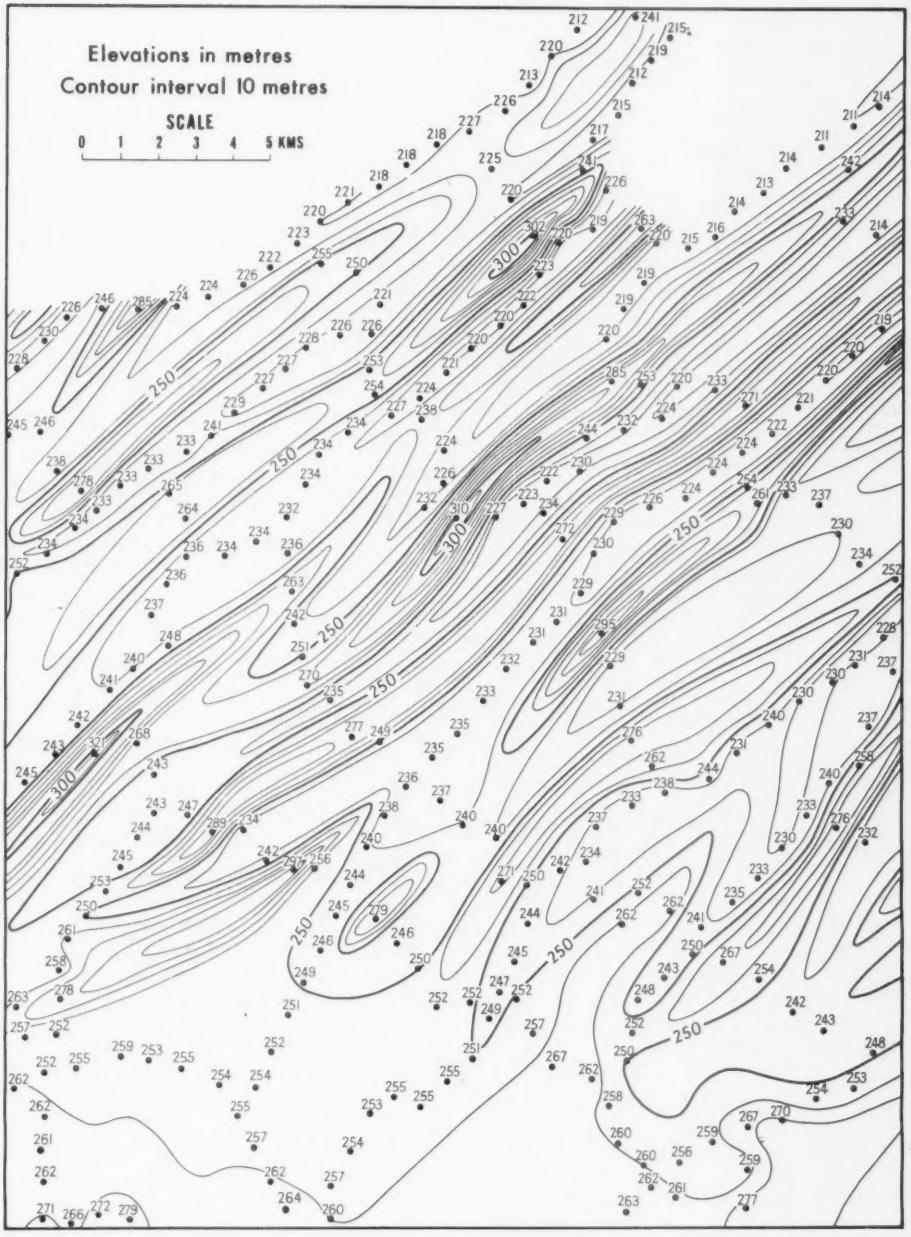

FIG. 2. Elevation map of sand area.

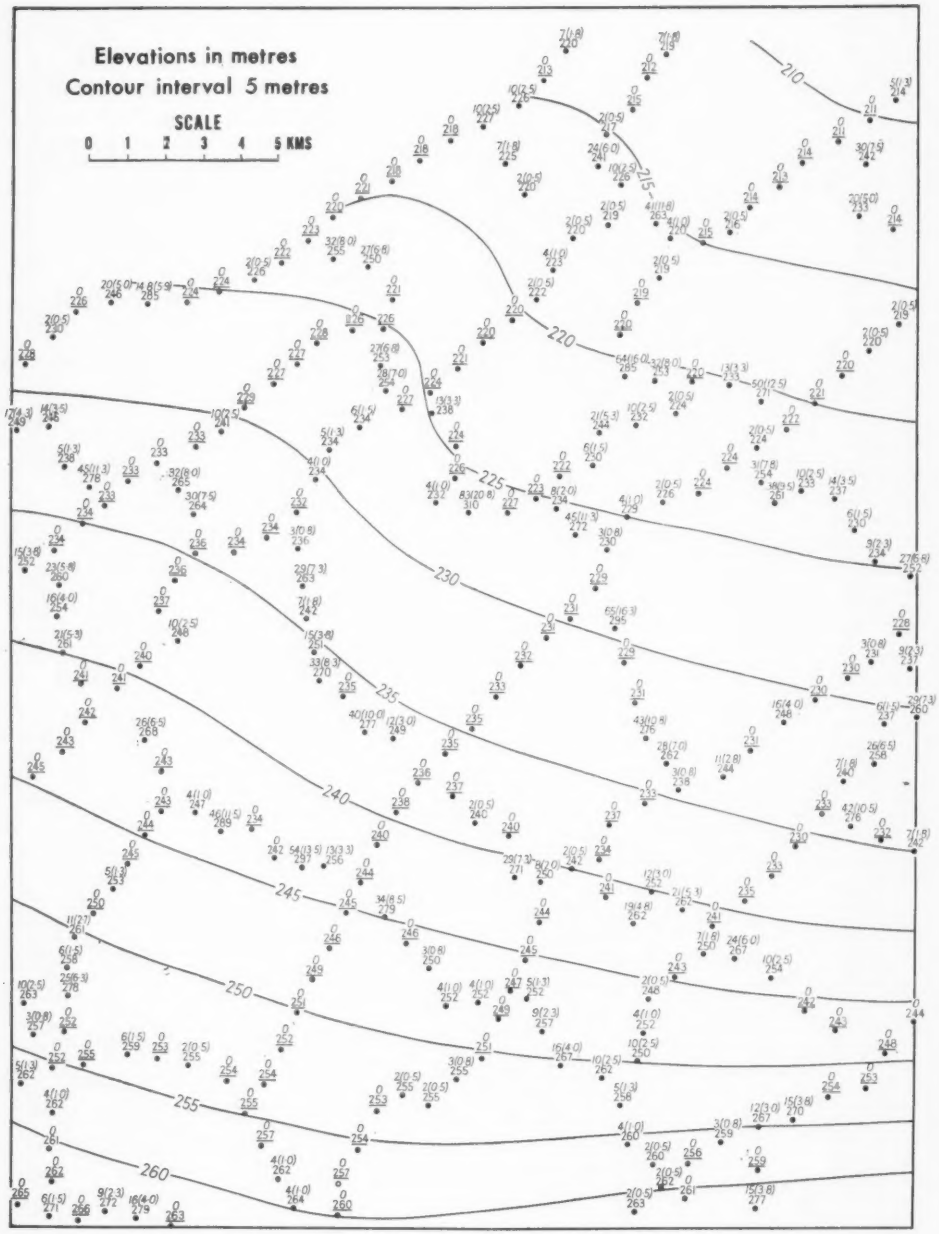

FIG. 3. Sand correction map.

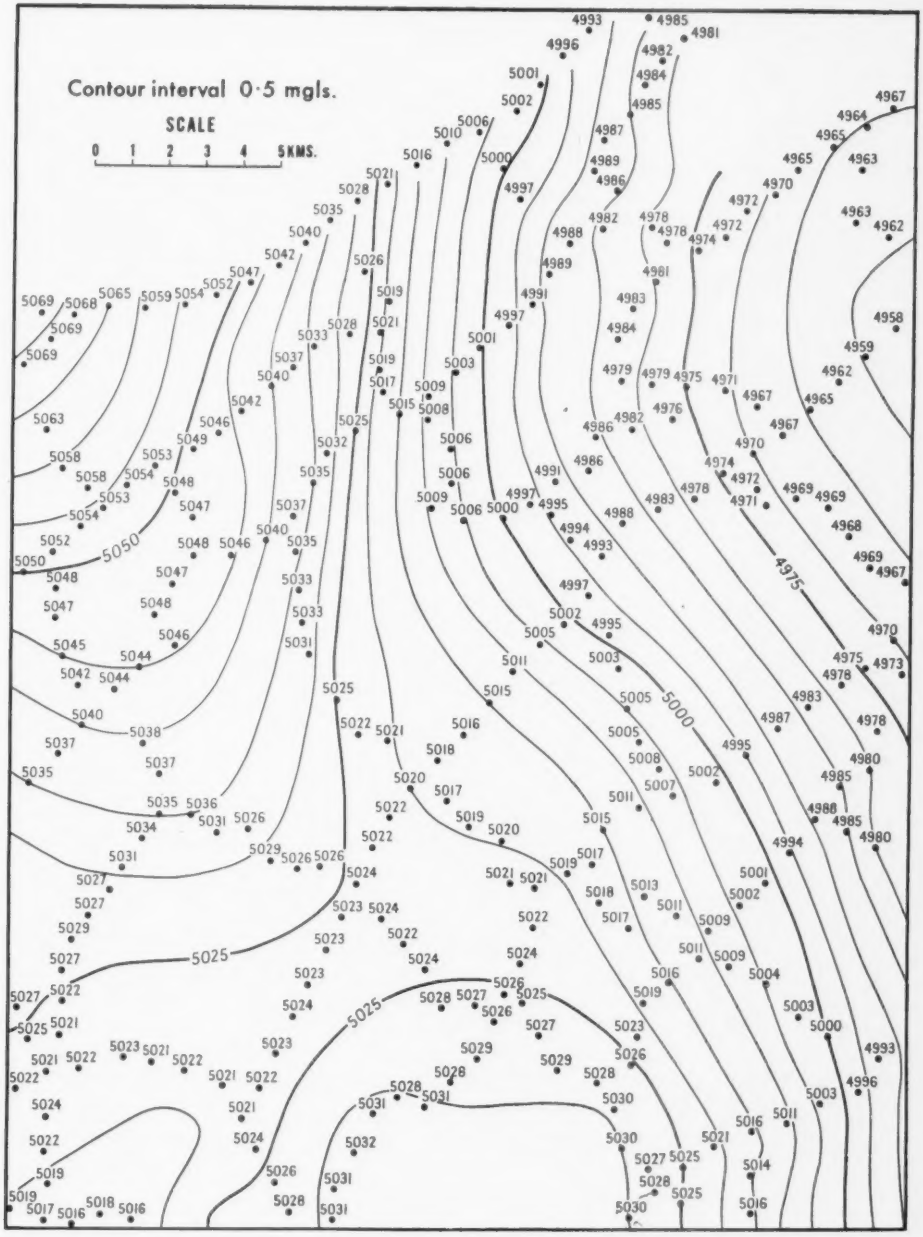

FIG. 4. Bouguer anomaly map of sand area.

sumed from the true "floor" will be regional in form. The final Bouguer Anomaly Map will still be smooth. Clearly, the method can be applied even to old surveys to arrive at a smooth progression of values although, if terrain corrections were not determined at the time of running the survey, some irregularities will still occur. As the Sand Correction is usually much greater than the Terrain Correction when the stations were reasonably sited, values will result that are much more easily contoured than hitherto.

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DEPARTMENTS

DISCUSSIONS AND COMMUNICATIONS

"The following paper by Dr. Charles C. Bates, Program Manager for VELA-UNIFORM, ARPA, was presented before the Society's 30th Annual International Meeting, Galveston, Texas, November 8, 1960. A preceding address by Brig. Gen. A. W. Betts, USA Director, Advanced Research Projects Agency (ARPA) more or less introduced Dr. Bates' more technological material by discussing the international political background of Project VELA-UNIFORM.

"The Editors of GEOPHYSICS feel that this material is vitally important in both national and international politics and specifically concerns geophysics of an exploratory nature. Such material is of essential interest to our membership, and the Editor is grateful to the authors for the privilege of publishing this somewhat nontechnical material as a discussion."

The Editor

VELA UNIFORM, THE NATION'S QUEST FOR BETTER DETECTION OF UNDERGROUND NUCLEAR EXPLOSIONS*

CHARLES C. BATES†

THE PROBLEM

Negotiations between the United States, the United Kingdom, and the USSR have been underway since October 31, 1958, a period of over two years, in an effort to reach agreement on a treaty for cessation of nuclear weapons' testing. It is United States policy to enter into such a treaty only if there is an effective control system policing such a ban. This paper provides a résumé of key technical events that have occurred with reference to the creation of such a control system, capable of detecting and identifying underground nuclear explosions. The paper also describes the VELA UNIFORM program, a widespread research and development effort under the over-all management of the Advanced Research Projects Agency, that is designed to improve markedly the state of the art in this particular technical field over the next two to three years.

Between July 1 and August 21, 1958, technical experts from the United States, United Kingdom, Canada, and France met with their counterparts from the USSR, Poland, Czechoslovakia, and Romania. After due deliberations, they unanimously recommended a nuclear test control system for consideration by the governments involved. The key detection techniques for underground and underwater nuclear explosions were seismic and hydroacoustic in nature, respectively. 170 to 180 control stations were proposed, 100 to 110 on continents, 60 on islands, and 10 on ships. The seismic equipment at each station, popularly referred to as a "Geneva-type Station," would include 3-component seismometers in the 1, 2, and 1–10 second period bands, a 10-unit vertical seismometer array at 1 second, and, in certain instances, a 3-component long-period seismometer at 25 seconds. Such stations would be 600 statute miles apart in seismically active areas and 1,000 miles apart in other regions. In addition to seismic detectors at each control point, the stations would have sensing devices for atmospheric pressure pulse, radioactive debris, electromagnetic signals, and, in coastal areas, acoustic detectors in the ocean's deep sound channel. In April 1960, the cost of establishing a world-wide control network

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† Nuclear Test Detection Office, Advanced Research Projects Agency, Washington 25, D. C.

over a 6-year period was estimated at about $1 billion and the annual operating cost at $250 million. Approximately 20,000 people would be required to operate the control system, all costs and personnel being shared by the participating countries. These estimates specifically exclude outer space detection techniques requiring the use of satellites. The number and location of the proposed stations is under discussion at Geneva; hence these cost estimates are quite speculative in nature.

With respect to the specific problem of detecting underground explosions, the 1958 estimates were based heavily on findings from the RAINIER shot of 1.7 kilotons in Nevada, the only underground explosion data available in mid-1958 to the Western scientists. The Conference of Experts concluded that seismic stations with considerably better than average noise conditions could not only detect the initial longitudinal seismic wave but also provide first motion criteria to a distance of 600 miles from the following types of explosions:

(1) Explosions of the order of one kiloton yield recorded during periods of favorable seismic noise conditions, and
(2) Explosions of the order of 5 kiloton yield recorded during periods of unfavorable seismic noise conditions.

The same capability would also exist in the "far zone" of detection at 1,250 to 2,000 miles from the shotpoint. Unfortunately, such a network would not only detect seismic impulses from explosions but also those from very numerous small earthquakes which give signals so similar to those from underground explosions that, as of now, only the first-motion criterion is useful in determining whether the signal was explosion- or earthquake-generated. This criterion is based upon the fact that, with most earthquakes being caused by linear slippage, the polarity of initial motion should differ with observational quadrant. In contrast, an explosion should give outward, compressional signals in all directions. Unfortunately, it has been found some earthquakes do likewise. Even worse, the sense of first motion is frequently lost in the background noise while the rest of the seismic signal is recorded, thereby giving a false sense of first motion. In addition, it is virtually impossible to differentiate between chemical and nuclear explosions at the present time. Hence, detected seismic events could be classified only as:

(1) Identified earthquakes, and
(2) Unidentified earthquakes and explosions.

In terms of identification capability, the Experts estimated that about 90 percent of all natural seismic signals equivalent to those from a buried 5-kiloton explosion could be identified as actually coming from earthquakes. A separate and conflicting estimate was given by the Experts that there would be only 20 to 100 unidentified seismic events of 5-kiloton equivalent or higher in continental areas annually, or that but two to 10 seismic events of that magnitude occurring annually within either the USSR or the United States would not be distinguished as to type of source. In such cases, actual on-site inspections would be required to ascertain definitely whether the signal came from a buried nuclear explosion, a large-scale chemical explosion, or an earthquake.

After the Conference of Experts adjourned, however, two new underground explosions, LOGAN and BLANCA, were fired under RAINIER-like conditions in late October 1958. Confined within a water-soaked volcanic tuff at a depth of about 800 ft, these three explosions of 1.7, 5, and 19 kiloton yields gave seismic signals having amplitudes equivalent to those from small shallow earthquakes of magnitude 4.0, 4.4, and 4.75, respectively. Furthermore, analysis of the data gave the somewhat startling result that the first-motion criterion was much more difficult to apply than had been previously thought. Using newly refined earthquake statistics which even now have an uncertainty of a factor of two because of the lack of standardized global seismic data, it became evident that the USSR, with about 6 percent of the world's earthquakes, could be expected to have about 280 seismic events of 5 kiloton or greater equivalent (RAINIER Coupling) annually. Of these events, only about 35 could definitely be identifiable as earthquakes. Thus, instead of the Experts' estimate of 2 to 10 unidentifiable events of 5-kiloton equivalent or greater, findings of the Air Force Technical Applications Center published in May 1960 indicated that there might be as few as 120 and as many as 490 unidentified events of greater than 5 kilotons within the USSR annually. Even in terms of Hiroshima-type explosions of 19 kiloton yield, 123 seismic events could be expected annually, of which 100 would be unidentifiable. As a consequence, the problem of maintaining adequate con-

trols by a formal nuclear test ban treaty appears much more difficult than originally thought.

Furthermore, the Geneva Conference of Experts did not consider the full implications of a violator's use of concealment techniques to degrade the capability of the control system even further. According to A. Latter of RAND, merely shooting in a medium harder than tuff, such as salt or granite, could reduce the expected seismic signal by as much as a factor of three or perhaps greater. Likewise, intermingling of nuclear seismic signals with those from a nearby contemporaneous earthquake or a series of large-scale chemical explosions would create much confusion. Perhaps the most effective way to avoid detection would be, however, to use the decoupling principle by firing the nuclear device in a cavity so large that the elastic limit of the wall is not exceeded and the outgoing seismic signal is reduced by one to two orders of magnitude as a result. Decoupling has actually been demonstrated to exist in special chemical explosions up to one ton in size. Reductions in seismic signal amplitude as great as 60 in Cornish granite and 120 in Louisiana salt were measured by the British and the AEC, respectively. Compared to the seismic signal in tuff, this would mean reduction in seismic amplitude of 120 to 300. The British have also obtained a reduction of four merely by adding a thermal absorber such as a water shield around the high explosive. Although the behaviors of chemical and nuclear explosions are not identical, experience to date suggests that the basic principle for achieving reduction in energy coupling in this manner is correct. The exact magnitude of the effect during nuclear explosions can only be found by actual field experiment. Thus, if seismic detection and identification techniques are to keep abreast of decoupling techniques, improvements by a factor of 100 to several thousand appear to be required in our capabilities not only to detect seismic events but also to identify their sources.

Once this technical problem came clearly into focus, a number of governmental decisions were made. Among the most important were these.

a. On December 28, 1958, at the request of the Secretary of State, the Special Assistant to the President for Science and Technology appointed a Panel on Seismic Improvement. This Panel reviewed the feasibility of improving the Geneva System. The Panel also considered the need for fundamental research on seismology and submitted a detailed report now known as the "Berkner Report" on March 31, 1959.

b. On January 5, 1959, the President's Science Advisory Committee stated that the analyses of data from underground nuclear explosives collected by the United States in the previous fall indicated that the capability of the Geneva Control System was considerably less than that estimated by the Conference of Experts.

c. On April 23, 1959, the Special Assistant to the President for Science and Technology met with the Deputy Secretary of Defense and the Chairman of the Atomic Energy Commission and agreed that specific recommendations of the Advisory Panels on High Altitude Detection and Seismic Improvement would be implemented. In the latter case, the Department of Defense accepted primary responsibility with the understanding that the Atomic Energy Commission would implement that portion of the program requiring nuclear explosions and any large chemical explosions conducted at NTS, in cooperation with the Department of Defense.

d. On September 2, 1959, the Secretary of Defense assigned the Advanced Research Projects Agency (ARPA) the responsibility for research, experimentation, and systems development to obtain at the earliest practicable date a system for the detection of nuclear explosions for both underground and high altitudes.

e. On October 2, 1959, ARPA issued the first work order to the Air Force Technical Applications Center for $835,000 for use on the seismic program, now given the title, VELA UNIFORM. On January 7, 1960, seven million dollars was added to this to complete the funding for FY 60.

f. On December 17, 1959, the Atomic Energy Commission began a three-month series of experiments known as Project COWBOY, using various sizes of chemical explosions in underground cavities located in the Carey salt mine at Winnfield, Louisiana. The results of these experiments confirmed the prediction that decoupling would significantly reduce the seismic signal, thereby making the underground detection problem more difficult than had originally been suspected.

g. On February 11, 1960, the United States proposed a "threshold" of seismic magnitude 4.75.

h. The Soviet Union responded to the United States proposal on March 16, 1960, and this led to discussions on the concept of the magnitude 4.75 "threshold."

i. On March 29, 1960, President Eisenhower and Prime Minister MacMillan of the United Kingdom released a communique which included the following points directly related to VELA UNIFORM:

   (1) There are great technical problems included in setting up a control system which would be effective in detecting underground nuclear tests below a certain size (less than seismic magnitude 4.75).

   (2) An agreed program of coordinated research undertaken by the USSR, United Kingdom, and the United States will lead in time to a solution of this problem.

   (3) The United States and the United Kingdom would be ready to institute a voluntary moratorium of agreed duration on nuclear tests below magnitude 4.75 as soon as the treaty was signed and arrangements made for a co-

ordinated research program for the purpose of progressively improving control methods for events below seismic magnitude 4.75.

(4) The United States and United Kingdom invited the USSR to join at once in making arrangements for a coordinated research program and in putting it into operation.

j. On April 19–22, 1960, subcommittees of the Congress' Joint Committee on Atomic Energy held extensive hearings on "Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Test Ban." In addition to a 77-page summary and 475 pages of published hearings, the Committee's staff issued a most comprehensive technical appendix including the Berkner Report, key documents from the Geneva conference, a report on unmanned seismic stations, and observational and theoretical studies pertaining to decoupling phenomena.

k. On May 7, 1960, President Eisenhower made public announcement of the VELA UNIFORM program. He stated the program would consist of a vastly expanded research and development program in the area of underground nuclear test detection and identification, including the use of nuclear and chemical research explosions underground for the purpose of testing out and improving today's techniques for detecting and identifying underground nuclear explosions. The President further noted that during Fiscal Year 61, the program would be funded at the rate of about $66 million.

During this entire period, diplomatic negotiations continued at Geneva, Switzerland, between the USSR, the United Kingdom, and the United States in an attempt to write a treaty which would initiate a formal agreement for the discontinuance of nuclear weapons testing backed up by a workable Test Ban Control System. This would replace the present de facto moratorium on nuclear weapon testing that has existed throughout the Geneva discussions. Following a five-week recess in August–September 1960, negotiations were reopened and continue at the present time. Although progress has been made on the development of a draft treaty and toward closing the gap between the two sides on a number of issues, many points remain unsolved. These include, among other things, the length of the formal moratorium over explosions below the 4.75 seismic threshold, the number of on-site inspections to be authorized for the purpose of checking unidentifiable seismic events, and the matter of conducting a coordinated research program, including the use of underground nuclear and chemical explosions to improve the detection and identification capabilities of the control system for smaller underground disturbances.

THE TECHNICAL APPROACH

If proper decisions are to be made concerning the long-term validity of the Test Ban Control System, drastic improvements in the science and technology of underground nuclear test detection and identification for events below seismic magnitude 4.75 are required before the end of the United States' proposed 36-month moratorium on such testing. In order to accomplish the necessary research as soon as practicable, the VELA UNIFORM program is employing a series of simultaneous approaches. These are

1. To drastically expand the effort, both national and international, in seismological and related research;
2. To improve markedly equipment and techniques for detecting and identifying subsurface nuclear explosions from a distance;
3. To develop and evaluate prototype seismic detection systems as modern as can be conceived with the present state-of-the-art;
4. To develop rapid, economical techniques for conducting on-site inspections to determine whether a suspicious event was actually a nuclear explosion or not; and
5. To conduct a carefully planned series of nuclear and chemical explosions underground for research purposes; the goal of such a series to determine quantitatively the limiting effects on detection and identification techniques of such major variables as depth, medium, type and size of energy source, propagation path, and degree of coupling; in addition, Project VELA personnel are to provide technical support to various elements of the Executive and Legislative Branches of the government.

While preparations for carrying out the VELA project have been proceeding for some time, no date has been fixed for actually conducting the planned explosion program. These experiments are not part of the nuclear weapons test program or the AEC's Plowshare program, which is concerned with possible peaceful uses of nuclear explosives.

The Berkner Panel Report, "The Need for Fundamental Research in Seismology," issued in March 1959, recommended a two-year effort in considerable detail that would have required $52,825,000 to meet goals of this type. The Panel's recommendations have provided valuable guidance in making up the present VELA UNIFORM program which, exclusive of nuclear explosion costs and certain close-in measurements, is being funded at the rate of about $33,000,000 per year. During Fiscal Year 1960, national participation in this program was such that industrial firms and nonprofit institutions, including uni-

versities, each received about 40 percent of the available funding, whereas in-house governmental participation required about 20 percent. The ratio in succeeding years may shift somewhat in favor of industrial participation as the impact of "hardware" developments is felt. The funding available for all types of participation will increase appreciably over the FY 60 level.

With respect to program management, ARPA has, of course, over-all management responsibility for the VELA Project. Within the program, the Atomic Energy Commission is responsible for providing the nuclear devices, the sites and cavities in which to fire the devices, the actual firing, and the making of measurements directly associated with such firing. In addition, similar support will be provided by AEC for all HE experiments at NTS. The Air Force Technical Applications Center not only serves as technical advisor to ARPA but also defines shot requirements, conducts and analyzes off-site detection measurements, assists in managing various research and development tasks, including those designed to improve on-site inspection techniques, and supervises the development and construction of experimental detection stations. The Defense Atomic Support Agency coordinates all Department of Defense activities at the various shot sites, manages the necessary on-site measurement programs to observe the conversion of shock energy to elastic energy, and executes all chemical explosions required outside the Nevada Test Site. The U. S. Coast and Geodetic Survey is responsible for providing standard seismic equipment in 125 selected stations throughout the world in order to obtain the long-missing standard seismic research data needed on a global basis. Data acquired in this fashion will be available to all researchers who indicate an interest in receiving it.

Top level technical advice is obtained from the Director of Defense Research and Engineering's Ad Hoc Group on Detection of Nuclear Detonations, of which Dr. R. Latter of RAND is chairman. Dr. F. Press is leader of the seismology subgroup and Dr. J. Crawford, Dr. J. Oliver, and Dr. H. Benioff are members. In addition, there will shortly be established a VELA Seismic Information Analysis Center at a research institute in order that there will be a small, highly qualified group of professionals having the necessary time to analyze all VELA UNIFORM technical reports quickly, provide timely digests of this information to all interested organizations, and to supply advisory opinions concerning technical implications of the digested material.

Prior to 1960 the field of low-frequency seismology in the United States received national support at the level of about $700,000 annually. Inasmuch as funds of this magnitude would buy but a fraction of just one modern long-range surveillance device, such as a radar or sonar, it is easy to conclude that the field of seismic detection has been much more fund-limited than have the fields of electro-magnetic or hydroacoustic detection. Yet the elements of all three surveillance techniques are based on well-established communications theory. In our case, it is necessary to understand the source, the nature of the propagation path, the effects of signal transmission along these paths, the best methods for detecting the signal at the receiving end, and, finally, the best methods for processing, analyzing, transmitting, and displaying the information acquired.

As far as seismic source mechanisms are concerned, there is still a dearth of comprehensive information concerning the exact nature of the manner in which seismic impulses are created by subsurface explosions, both nuclear and large-scale chemical, both tamped and untamped, as well as the effects of varying media depths, geology, and topography. Some of the key areas requiring further study are listed in Table I. To reduce the "false alarm" rate of any detection system caused by earthquakes, much additional study is required on such phenomena as polarity of motion in various quadrants from earthquakes, particularly since previous investigators have stressed earthquakes with magnitudes much greater than those pertinent to the present nuclear test detection problem. Moreover, with investigations of the past using observations acquired with a varied assortment of inadequate, nonuniform detectors in a few localized areas (California, New Zealand and Japan, for example), important work remains to be done before the true radiation pattern of elastic energy from small earthquakes is known on a global basis. The data from the global network of 125 seismic stations should provide requisite data for such studies. Techniques for determining depth of focus are rather crude. Likewise, such a fundamental physical quantity as the amount of seismic energy released in an earth-

Table I. Gaps in Present Knowledge of Large-Scale Explosion Dynamics

1. Equation of State for Geologic Formations
2. Close-In Displacements Through Entire Event
3. Hydrodynamics of Non-Linear Region Prior to Elastic Zone
4. Difference in Body Sfc. Waves by Varying
   a. Explosion Yield,
   b. Medium,
   c. Depth of Burial,
   d. Local Geology and Topography, and
   e. Cavity Size and Shape
5. Differences in Nuclear and High Explosive Sources
   a. Intensity Difference for Given Yield,
   b. Size of Resulting Cavity,
   c. Strength and Signal Character, and
   d. Symmetry
6. Differences in Nuclear and Earthquake Impulses
   a. Signal Character and Duration,
   b. Post-Impulse Behavior, and
   c. Depth Control

quake cannot be determined to within a factor of 10 or more. Moreover, much more needs to be known about the nature of the often weak aftershock sequences before they can become a valuable discriminating device. Table II shows the work currently underway in this important area of investigation.

With respect to studies of the propagation path, scientific principles dictate that the nature and layering of the vibrating media must be known if appropriate constants are to be inserted into the theory explaining wave behavior along the various paths to the detector. There is still considerable question as to the actual number of layers in the earth's crust. A two-layer crust has been favored in the United States. In Alberta and Iceland three layers appear to be present. In central Russia five crustal layers are reported, as well as three in the supposedly homogeneous mantle beneath. As of last year, however, Woollard reported that there were but twenty sets of well-conducted measurements of crustal structure in the entire United States. Although some of the complicating effects of propagation can be eliminated by studying surface waves having wave lengths so long, i.e., 30 km and up, that local geological variations along the path become insignificant, higher frequency waves of 0.5 to 5 cps must still be used for accurate location fixes. Just as in sonar and electromagnetic radiation, scientists and engineers need to pursue actively both ends of the frequency spectrum in order to achieve somewhat different but complementary goals. The possibility exists that a truly comprehensive understanding of the nature of the earth's crust and upper mantle in the Western and Southern United States will be needed before we can really understand the results obtained with the six prototype Geneva-type seismic detection stations planned to bracket the Nevada test site. The same applies to results from the several long lines of temporary seismic stations radiating out from ground zero that will be manned for the research explosion series. Once propagation behavior is well understood over this variable expanse of continental platform, it should be possible to do a much better job of designing a workable global system of seismic detectors. The crustal studies presently sponsored by VELA UNIFORM are listed in Table III.

Our capability to understand fully what goes on during propagation of seismic energy away from an underground nuclear explosion is severely hampered by the fact that although the initial shock wave is relatively simple and short-lived, the resulting elastic wave quickly becomes a series of complex, often overlapping, combinations of direct, reflected, refracted, and diffracted pulses with periods ranging up to 100 seconds or more. These various kinds of waves are scattered,

Table II. VELA UNIFORM Research Contracts (Oct. 1, 1960)
Seismic Source Mechanisms

Activity	Type of Work	Funding ($1,000's)
Univ. Calif. (Berkeley)	Seismic waves from small earth quakes; Nature of aftershocks	406
Penn. State Univ.	Model studies of radiation patterns	7
St. Louis Univ.	Shear Waves from Small Explosions	37
	Source Mechanism Using Other than "P" Waves	≈50
Columbia Univ.	Generating mechanism using intermediate and long-period waves	350
Mich. Univ.	High-frequency Noise in Wells ~1,500 Ft Depth	23
United Electrodynamics	Variation of Seismic Noise and Signals with Geologic-Geographic Environment	191

Table III. VELA UNIFORM Research Contracts (Oct. 1, 1960)
Propagation Paths

Activity	Type of Work	Funding
		($1,000's)
U. S. Geol. Survey	Western U. S. Crustal Structure by Refraction shooting	311
St. Louis Univ.	Phase Velocities Central U. S.	≈160
Cal. Tech-UCLA	Phase Velocities Various Mtn. Regions	≈ 80

Table IV. VELA UNIFORM Research Contracts (Oct. 1, 1960)
Seismic Propagation Phenomena

Activity	Type of Work	Funding
		($1,000's)
Cal. Tech-UCLA	Transfer Functions Typical Crustal Structures	≈20
Cal. Tech	Inverse Transforms for Long-Period Waves	≈150

Table V. VELA UNIFORM Research Contracts (Oct. 1, 1960)
Seismic Signal Detectors

Activity	Type of Work	Funding
		($1,000's)
Columbia Univ.	Improved Long-period Detectors Discriminating Against 4–10 Sec. Microseisms	50
Cal. Tech.	Direct Digitizing Seismograph More Stable Long-period Seismograph	90
Geotech Corp.	Improved General Purpose Siesmographs Special Purpose Seismographs for Remote Operation or Rapid Deployment	116
Texas Instruments	Practical Method for Information Display from Seismometer Array	170

distorted, dispersed, selectively attenuated, mode-converted, and mixed with a generous portion of unrelated background noise. The work currently underway in this complex field is shown in Table IV.

Low-frequency seismic detectors have normally been peaked to respond to a particular frequency band within the broad frequency spectrum which ranges from 10 cps down to 0.0025 cps. Such detectors have also been almost always used singly per component of motion. If the history of reflection seismology can be used as a criterion, the improvement and multiple use of seismic detectors actually has a long way to go before the law of diminishing returns sets in. One of the most attractive approaches, which United Electrodynamics has already demonstrated under AFTAC sponsorship, involves the use of deep-well seismometers. In fact, theory suggests that improvements in signal-to-noise ratios of the order of 50 are possible by moving from the surface to depths approximating 10,000 ft. The well-seismometer approach is particularly attractive in noisy areas and where the installation of arrays is difficult from an engineering and construction standpoint. The ocean floor also appears theoretically attractive. Pressure measurements by Munk suggest that the 30-second period region might be particularly quiet as far as background noise is concerned. Oliver also points out the possibility that sea-mounts might act like exponential horns for body waves of about 1-second periods, as well as the fact that the low shear velocity of the soft sedimentary layer suggests that an efficient wave guide for short period waves might also be possible in this layer. However, as you can see from Table V, VELA UNIFORM's effort to date falls entirely in improving surface-based detectors. Moreover, break-throughs are needed in the field of on-site inspection techniques. Today's most sophisticated geophysical detectors, as listed in Table VI, are hard-pushed to locate quickly a radioactive zone 100 to 500 ft across at depths of 1,000 to 5,000 ft unless the violator has left visible

Table VI. Contributing Techniques to On-Site Inspection

1. Observation of Local Culture
2. Mensuration
3. Photo Analysis
4. Geochemical Analysis
5. Seismic Noise Monitoring
6. Logging
   a. Acoustic
   b. Neutron
   c. Geothermal
7. Surveys
   a. Radiation
   b. Electrical
   c. Magnetic
   d. Infrared
   e. Gravity
   f. Precision Leveling
   g. Seismic

artifacts within the suspicious area which can easily be 6 to 12 miles on the side.

With respect to the area of signal analysis and data display, some of the most exciting work is likely to fall in the area of developing techniques which clearly demonstrate the sense of motion at the origin. Much work of this general type is currently going on in various areas and is termed "inverse filtering," "equalization and pulse shaping," "phase compensation," "deconvolution." All are filter techniques in a sense. It is believed that the limitations of the method have not yet been reached in practice.

Other approaches that need to be pursued are data displays using continuous array, spectral, and Fourier analyses to supplement the traditional amplitude and phase criteria for signal "picking," as well as four-dimensional data presentations such as can be obtained in the "Iconorama" method used to display air defense activities. The work actually funded in signal analysis and display at the present time is listed in Table VII.

It is obvious that the problem of discriminating between bursts of seismic energy caused by explosions and those caused by earthquakes of equivalent magnitude could be greatly reduced if a definitive check method utilizing some other kind of energy pulse were also developed. Two possible methods suggest themselves, electromagnetic impulses through the earth and atmospheric pulses observable on sensitive microbarographs. Although theory and routine experience suggest that neither type of signal can be detected at any great distance; nevertheless, they have been observed to exist upon occasion. A Hughes Aircraft study has also suggested that the detection capability would be definitely increased by placing the detectors in holes of at least 1,000 ft depth. Hence, better observations of these signals are scheduled for the first underground nuclear explosion currently planned in the research series.

Hydroacoustic detection is a possibility, it being known that waves of coastal earthquakes can be transmitted across water areas as T-waves with the speed of acoustic energy through water and a period of about 1 cps. This type of coupling between land mass and ocean boundary will also be looked for during the planned research explosion series. There is also the untouched area of investigating ways in which to identify better underwater nuclear explosions in shallow or sheltered water areas.

In the area of prototype seismic detection systems, the Geotechnical Corporation has already constructed the first known Geneva-type seismic detection station. Located near Fort Sill, Oklahoma, this station—the Wichita Falls Seismological Observatory—was officially opened October 13, 1960. It would be joined by five sister stations located in the western United States according to the Geneva-recommended 600-mile spacing. Also, on September 15, 1960, the Air Material Command announced the award to the United Electrodynamics-General Telephone team

Table VII. VELA UNIFORM Research Contracts (Oct. 1, 1960)
Signal Analysis and Data Display

Activity	Type of Work	Funding ($1,000's)
Univ. Calif. (La Jolla)	Characteristics Microseismic Noise and Ocean Bottom Signals Methods for Distinguishing Seismic Signals in Noise	418
Univ. Mich.	Spectrum and Attenuation of Waves from Small Earthquakes and Explosions	177
Cal. Tech.	Development Hi-Speed Digital Techniques	≈150
Columbia Univ.	Development Hi-Speed Computation Techniques	≈150
Mass. Inst. Tech.	Cross-correlation Techniques for First Motion of "P" Waves	42

for design and site evaluation of the most advanced seismic detector array and recording facility yet conceived—the 100-unit array proposed by the Berkner Panel, plus an associated Systems Development Laboratory. Work in the area of unmanned and simplified manned seismic detector stations is planned, as is a data analysis center for the VELA UNIFORM shot program and a seismometer calibration facility.

One of the most important phases of Project VELA is the planned series of underground nuclear and chemical explosions. In the United States, only three underground nuclear explosions greater than 1 kiloton took place befor the United States ceased all nuclear testing on October 30, 1958. All were in small rooms, in identical material, and exploded at essentially the same depth. As a result, there is still much uncertainty as to how the energy conversion from the shock to elastic wave actually occurs under differing environments, as well as an urgent need to verify the effectiveness of our present detection and on-site inspection techniques and concepts.

The total programmed series of these underground research explosions calls for 11 to 13 nuclear detonations and at least 11 chemical detonations, the major portion of which will be tamped explosions. The effect of yield magnitude will be investigated by a series of tamped scaling shots employing nuclear devices in both tuff and in salt. Some decoupling shots will also be detonated.

Extensive instrumentation for measuring the close-in dynamics of underground explosions will be used in this series. Because many of the instruments must be in holes, shafts, or tunnels; the cost of these close-in observations is high. Off-site, the Air Force Technical Applications Center has arranged a comprehensive seismic measurement program in the region of strong-motion and along lines radiating out for thousands of miles from the shotpoint. These off-site observation posts are specially equipped with sensors capable of detecting 3-component earth motion in various parts of the frequency spectrum between 0.01 and 10 cps. Electromagnetic and microbarographic measurements by several contractors are also planned by AFTAC to determine whether detection of these phenomena can be developed into techniques for checking the seismic method. On-site inspection techniques; aerial, surface, and subsurface; will also be tested on each explosion site to determine whether more feasible ways can be developed than those that presently exist.

In summary, it has been related how VELA UNIFORM, in an effort to generate quickly technical solutions that will answer urgent questions posed by the government, has been developing into the largest national effort yet known in the field of terrestrial science. It is hoped that the assignment of technical goals, the availability of adequate funding, the sense of urgency, and the existence of applicable scientific knowledge and technical know-how in both seismology and its related fields will prove to have been what was required in providing the answers the nation asked of the earth science fraternity.

NOTES ON THE SESSION ON GOVERNMENT SCIENCE AT THE SEG CONVENTION IN GALVESTON, TEXAS, NOVEMBER 1960*

F. A. VAN MELLE

Abstract: The history of the attempts at seismic control of nuclear tests shows that even before the discovery of decoupling or muffling—known in seismic exploration from shooting in a dry cavity—of explosions, the state of the art favored the cheating nation. With muffling, detection lags concealment of small nuclear tests by a factor in excess of one hundred.

Technical and political considerations cannot be separated. A multibillion dollar effort such as the 180 seismic-station Geneva system should not be undertaken without virtual certainty of adequate detection. If delays in construction, operation, and in situ inspection rendered the program ineffective within Russia and China after the free world had spent billions on the network in other parts of the world; the West would have suffered a sensitive cold war defeat and incurred the resentment of the underdeveloped nations. It would face frustration and loss of confidence at home. A fraction of the number of Geneva stations within the U.S.S.R., supplemented by a world-wide net of seismological observatories of universities and other bodies with standard modern equipment and exchange of personnel and data, would have all the indirect advantages claimed by Dr. H. Bethe for the full Geneva system.

A break-through in research to advance detection by a factor in excess of one hundred is needed before an effort of DEW line magnitude appears justified. The probability of radical break-throughs in research is never large. This diminishes the importance of attempts to improve detection by factors of two or three and of auxiliary development projects, such as those connected with on-site inspection which presuppose effective seismic detection by a world-wide net of stations.

At the annual convention of the Society of Exploration Geophysicists in Galveston, Texas, in November 1960, the exploration geophysicists showed great interest in a series of papers grouped as "Government Science." This session, which dealt largely with the detection of nuclear tests—a problem of world-wide importance under any nuclear test ban—was among the best attended of the entire convention. A paper accepted for publication in GEOPHYSICS (Gudzin and Hamilton, 1961) describes the first seismograph station specifically designed for the detection of nuclear blasts set off below the surface of the earth.

The readers will be more or less familiar with the history of the protracted negotiations between the great powers on the subject of an effective control system to accompany a future agreement on the cessation of nuclear testing extending the present moratorium.

In 1958 at Geneva, the Soviet experts were constantly more optimistic than the Western experts, stating in effect that reliable seismic control can be achieved with a loose net of stations. The subsequent discovery of decoupling[1] by United States experts proved how justified the cautious attitude of the free world was. Before this discovery, the Geneva experts had drawn up a plan for a world-wide network of 180 stations, 22 of which would be located within the U.S.S.R. Together with on-site inspection of suspicious events, this would have a fair, according to the Western experts, to excellent, say the Soviets, chance of detecting explosions above 5 kilotons under "Rainier" coupling. This means tight packing in relatively soft rock (tuff) as in the 1.7-kiloton,

[1] Muffling of explosions by placing the charge in the center of a cavity of 91,000 or more cubic yards per kiloton, which works out to a hole diameter of 170 ft or over for maximum concealment of one kiloton (no appreciable gain by larger cavities). This reduces the elastic energy yielded by a one-kiloton explosion to that of about 8 tons tightly packed in the same rock (less than one percent). This theory was experimentally confirmed by the so-called Cowboy Series of Tests, chemical explosions in holes in the salt of the Carey Salt Mine near Winnfield, Louisiana. Exploration seismologists will recognize the effect of shooting in a dry cavity.

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September 1957, Rainier test in Nevada, the only test on which the 1958 Geneva experts had exact seismic data as a base for their discussions. After the discovery of decoupling, effective detection of explosions in the 1–5 kiloton range became obviously impossible with the original 180 stations, but Dr. Hans Bethe estimated that an additional 600 (or perhaps only 200 concentrated in seismically active areas) unmanned stations within the U.S.S.R. would allow a measure of control of decoupled explosions of 20 kilotons. This is equivalent to 70 tons with Rainier-coupling or 170 tons tamped in salt. The number of earthquakes of such low energy which occur yearly within the U.S.S.R. is estimated at 5,000, of which some 90 percent could presumably be identified as earthquakes. The 10 percent unidentified events still would number 500, requiring a large number of on-site inspections, each of which would cost millions of dollars. There is here, firstly, a political problem. The Russians (July 1960) will consider only three such inspections yearly and are unlikely to change this position. Secondly, there is an economic problem; the cost of the installation of the 22 Geneva-type stations in the Soviet Union alone has been estimated by an engineering firm at one billion dollars or even more, five billion for the 180 world-wide stations. Thirdly, there is the problem of the explosions in the 1-kiloton range which the Geneva system cannot monitor but which we cannot fire in secret because this is an open country with a free press, whereas there is no effective seismic control system to find out whether the Russians live up to their promise to stop testing under the present moratorium. Finally, France, rumored to be joined soon by Red China, is conducting tests at present. A project beset with all these uncertainties hardly deserves to be mentioned in one breath with the DEW line project, the line of Distant Early Warning chain of radar stations in the far North, as it is on page 12 of the "Summary Analysis of Hearings" April 19–22, 1960, before the Joint Congressional Committee on Atomic Energy where it says, "The project is compared in engineering difficulty to the multibillion DEW line project. . . . "

These difficulties and uncertainties were not sufficiently emphasized at Galveston. Although one of the papers dealt specifically with decoupling, an unprepared listener was left with the general impression that the project had a good chance to make a positive contribution to the peace of the world. The reports in the trade journals reflected this same feeling. An explanation for this optimism is near at hand. We are all grasping at straws to remove the threat to our existence posed by nuclear warfare and by the release of radioactive poisons by continued, above ground, nuclear testing. Those actively engaged in the project feel a noble urge to lead humanity out of an impasse. For this, the prophets of old and the founding fathers risked their lives and sacred honor. But now—maybe—such a contribution can be made in safety, honor, and affluence. This burdens all concerned with the project with duties of hard, unbiased thinking; duties which are shared by the not professionally involved responsible citizen, who in a free country can make his voice heard by government and fellow men. Unbiased thinking is a rare commodity at all times and especially rare in peace time democracies, which—we fear—would present to a hypothetical disinterested observer the picture of a camp full of confusion with countless men so busy grinding their little axes that they hardly notice what is going on around them. To prepare ourselves for the task of assessing the difficult nuclear disarmament problem correctly, we may examine a few aspects of it a little more closely.

When, in the abbreviated record of the Congressional proceedings, an engineering report is quoted to the effect that the cost of this project will be comparable to that of the DEW line system, the implication should be questioned that its value to the free world will be comparable. The two projects are not comparable; political obstruction by a potentially hostile host does not affect the functioning of the DEW line.

The vulnerable points of the project; "jamming" of seismic stations by man-made noises, small explosions to mask the direction of the first kick, Russian experiments carried out in China, Russian restrictions on in situ inspections to the point of reducing control to ineffectiveness, possibility of delays in construction caused by lack of cooperation by the Russians (or Chinese!) as contrasted with construction on friendly soil, and many others can be found in the full account of the Hearings of the Joint Congressional Committee on Atomic Energy, April 19–22, 1960 (950 pages). Owing to our desire for peace and security, combined with other human characteristics, these flaws, loopholes, and obstacles receive less and less

emphasis as one gets further from the source. The British proposal of a three-phase plan for the 180-station world-wide network (September 1960) is not reassuring. It reflects "pre-decoupling" optimism. As the technical situation is at present, the investment of billions and of our equally or more precious technical man power, with the three on-site inspections the Russians will allow—could not even accomplish the probable detection of a nuclear explosion of 20 kilotons (Hiroshima and Nagasaki size), leaving the 0.5- to 5-kiloton range entirely in the (Russian) word-of-honor range. And the kiloton range may well be where the most important military developments remain to be made. Our scientists do not agree on this point. There appears to be two schools of thought among them; one, which maintains that we need to continue testing for military purposes in the kiloton range, Teller and others represent this school; the other, represented by Bethe, which maintains that we need not. Since the Russians will do as they choose in this field, controls or no controls, the case for a multibillion dollar control system which still can be cheated is rather weak. If the "go-on-testing" school is completely right (meaning that we have practically everything to learn in the kiloton field), then insistence on a lower permissible limit appears necessary. Unlike the Russians and Chinese, we cannot resort to clandestine tests. If the "stop-now" school is right or essentially right (meaning that we are well advanced in the technology of kiloton weapons), then the world can only gain by an agreement to stop all nuclear testing between us and the Russians. It would not matter whether the Russians cheat in the kiloton field. Should they be behind, their military will insist anyway on "rising" to an adequately lethal level, agreement or no agreement, moratorium or no moratorium. The position that we and the world can only gain by an agreement to stop nuclear testing was eloquently advocated by Dr. H. Bethe in the August, 1960, issue of the *Atlantic Monthly*. He maintains that such an agreement would, more than any other arrangement, tend to limit the nuclear club to the existing members and points out that admitting stations, and even inspections on their territory, is an unprecedented concession from the Russian side. He admits that cheating in the kiloton range would still be possible, but yet—and here it is difficult to see his point—advocates building all 22 stations within Russia and presumably therefore, all 180 world-wide stations of the Geneva system. An engineering firm has submitted five billions as an estimate of the cost of the world-wide system (Hearings, p. 320). The indirect advantages which Dr. Bethe claims for an agreement to stop testing could be achieved by as little as one-third of the 22 stations within Russia. The six stations above the Chinese border, numbers 15, 16, 17, 18, 19, and 22 of the Geneva system,[2] together with the number of inspections (three) which Ambassador Tsarapkin mentioned as permissible (p. 219 of the "Hearings . . . ") would serve the purpose envisaged by Dr. Bethe. Such a reduction would moreover meet the objections of the Russians who claim (Geneva, September 1960) that 22 (or 21) stations on their territory are too many.

It is not reassuring to find diametrically opposite opinions among our foremost experts. Such a divergence of opinion usually indicates a bias somewhere. A citizen who hears sums like five billion dollars mentioned in a casual way[3] wants, understandably, to find out which side presents the better arguments, other than economic ones. It would seem that the arguments of the "stop-now" school are the more cogent ones. The flat statement by Dr. Bethe, in his *Atlantic Monthly* article, that we have all kinds of small nuclear

[2] The numbers from "Hearings . . . , " map on p. 319. In the "Summary Analysis . . . " of the same hearings the same numbers appear on page 41, different ones on page 34.

[3] In the "Hearings . . . , " page 320, a contractor estimates the cost of the stations within Russia at one billion dollars, the cost of the world-wide system at five billion dollars, but the "Summary Analysis . . . " of the same hearings (where one finds the 950 pages of original testimony condensed to 78 pages) contains on page 12 the statement that the report in question estimated the cost of the control posts in the Soviet Union alone at one to five billion dollars. Four or five billion dollars apparently did not bother anybody particularly, even Dr. Bethe in his article in the *Atlantic Monthly* quotes on page 48 the erroneous figure of five billion dollars for the Soviet Union alone. In order not to quote him out of context it should be mentioned that he discussed a new engineering estimate to the effect that 200 unmanned plus 20 large basic stations in the U.S.S.R. could be built for one-half billion, to which he adds "this is not cheap, but a great deal less than the one to five billion dollars for the large stations alone mentioned in the . . . hearings in April (1960)." Did anybody ever pause to guess at the cost of the 180 stations when they read that 22 of them could cost five billions? The contractor also assumes that we are going to build the stations within Russia ("Hearings . . . , " p. 321), and presumably pay for them. Are we?

weapons, weapons that can be fired from fighter planes, from big guns, or as infantry rockets, is supported by news releases which we have seen from time to time. We can hardly assume that the published pictures and stories of such weapons were intended to deceive the world. Deception which spurs one's opponent to greater effort does not make sense. The official position of the U.S.A. at the three-power nuclear test ban conference in Geneva also seems to lean to Dr. Bethe's views. There we proposed in September 1960, a 27-month moratorium on small underground explosions to be effective after signing of a treaty outlawing all nuclear tests except small underground explosions.

But regardless of whether the "go-on-testing" or the "stop-now" school is right, the 180-station system of the Geneva experts can only lead to a sensitive cold war defeat of the West. To offset decoupling in the face of a limited number of stations (less than 22, Russia at Geneva, September 1960) and inspections (three seems to be all the Russians will allow) nothing less than a breakthrough is needed in detection techniques to improve detection by a factor in excess of one hundred, probably by about five hundred. It is fine to witness such "dynamic optimism" as that of Dr. Richard E. Roberts, of the Carnegie Institution, who ("Hearings . . ., " p. 194) stated that he licked worse problems in the past, but research break-throughs are not made on order. He can expect improvement by a factor of a few from development type research which is all that unlimited funds will buy. To assume that a major frontal attack will provide a break-through is contrary to all experience in the history of science. For instance, when the optical microscope neared the limit of its resolving power, neither the frontal attack by a refined theory of lenses and by immersion techniques nor even the Nobel-prize winning application of diffraction yielded more than a factor of a few. A generation passed until the electron microscope effected a break-through into the realm of smaller dimensions. Break-throughs come through fundamental research leading to developments in other, sometimes apparently remote, fields of endeavor. They provide the unforeseen Remagen Bridge over which the forces of knowledge penetrate into the dark hinterland of the unknown. As one researcher asked: who, before carbon 14 dating was known, could have predicted that research on cosmic rays would open the way to more accurate age determinations of Egyptian mummies? Yet we find on page 36 of the "Summary Analysis" the statement that "The Panel[4] concluded that about three years of research effort would 'probably result in future improvements which could achieve the same capability in the Geneva net of 180 stations as was originally (i.e. before decoupling was discovered) estimated by the Geneva Conference of Experts.' " I was unable to find this statement in the summary report of the Berkner panel report as it is given in the "Hearings. . . ," p. 643–839, where we find much more cautious prognostications. But it does not really matter where the statement originated. What matters is what is found in the "Summary Analysis . . ." (the busy men who guide our destinies do not have time to read anything except summaries). So on December 18, 1960, the nation heard John A. McCone, Chairman of the AEC, on a TV program, voice the opinion that in a few years research is expected to bring detection to the point that explosions [of 20 kilotons], equivalent to 4.75 magnitude earthquakes, will be monitored effectively by the Geneva 180-station system, supplemented by 20 inspections yearly within the U.S.S.R. This is the same statement of page 41 of the "Summary Analysis . . . ," in different words. We are apparently going to bring about a breakthrough in science by unlimited appropriations! In reality, the task escapes the frontal attack. After securing a gain in a factor of a few, perhaps even ten, we can do no more than give our graduates in science an awareness of the problem so that they will not overlook a bridge, should it loom in the darkness.

One of the gambits in the chess game of the cold war is to lure the opponent into wasting his resources on sterile pursuits. This is especially effective when the ultimately sterile pursuit was initiated with high hopes. Few things are as demoralizing or do as much to soften one's fiber as being picked up and then let down. In the chess game of the cold war, one can expect attempts to make us mass our forces against a flank position which can be made impregnable by a simple move. The Russian position that the entire multibillion

[4] The Panel on Seismic Improvement under the chairmanship of Dr. Lloyd V. Berkner.

network should be built before it becomes operative suggests that maneuver. Also, in a chess game we try to push enemy knights to the edge of the board where they are only half effective. Our engineers are our knights.

To make a supreme effort of money and man power under circumstances where we can be fooled and disappointed is unimaginative Maginot-line thinking, psychologically unworthy of the leaders of the free world. What will be the effect on the underdeveloped nations of the free world if we spend five billion dollars for construction, plus the estimated quarter of a billion dollars yearly for operations, then are made the target of ridicule by the Russians or the Chinese who could demonstrate how they fooled us, for instance, by unveiling a lightweight, relatively "clean" tactical weapon in the kiloton range developed in spite of our best, but selfish, efforts? Such a "clean" weapon would not arouse the indignation of the peoples of the world because it would not endanger all life on earth. Would we threaten massive retaliation with weapons that do so?

In short, a wealthy nation does not have the moral right to grasp at a multibillion-dollar straw. If we want to do unprecedented things and risk being fooled, let us risk becoming noble fools. We could ask the underdeveloped nations if they will cancel custom duties and taxes, cut all red tape, publish all construction costs in the building of four billion dollars worth of schools and hospitals (and roads to connect them) as fast as they can train teachers and medical personnel with our help. The nations themselves would, where necessary, institute land reforms—as McArthur carried them out in Japan (these the good Uncle should not finance under any circumstances). "We technical people should not engage in politics," someone says, "and these remarks are political." But by discussing a doubtful multibillion-dollar project as if it is a good bet, we are already in politics. Besides, this is a subject which cannot be studied without considering political and psychological realities. Then we see that, when the risks of failure would weaken us in the eyes of the world, successful technical performance should be assured before we embark on a project. In other words, the technical specifications have to be commensurate with the political consequences of failure, and these consequences worsen proportionally to the size of our investment. Our investment should be kept down to a size where it does not alienate the poor peoples of the world. As things look now, we stand to pay for the capacity to identify 10 percent of the suspicious seismic events that could be nuclear explosions by losing 90 percent of our friends. We are living in a glass house, and the poor people of the world are looking in at our parties.

Under the present circumstances, although decoupled tests in the kiloton range cannot be detected, there still remains, as Dr. Bethe has pointed out, possibilities which it is our moral duty to pursue. Based on the information available to the general public, the following conclusions seem warranted:

(1) Before all, agreement should be sought to outlaw and abolish nuclear tests above ground and in the ocean where they endanger organic life on earth.

(2) When Dr. Bethe is right in his statement that we are well advanced in the technology of tactical or kiloton weapons (a field in which we cannot prevent the Russians from catching up), we do not lose anything by extending the moratorium on small underground tests as long as the Russians prove their good faith by cooperating in the construction of a number of Geneva-type stations within the U.S.S.R., the U.S.A., and Great Britain and by making every station operative as soon as it is completed. Should the "go-on-testing" school be right in that we risk to fall seriously behind the Russians by not testing any more kiloton weapons, then we should carry out the required small tests undergound as soon as possible, after which we can negotiate with the Russians on that foot of equality, which according to Dr. Bethe already exists. But we cannot risk giving a dictator or dictatorial group the feeling of military superiority. It is well to remember Hitler's reasoning—that flabby democracy—an election year—that must be einfach—etc.

(3) The U. S. Coast and Geodetic Survey is now embarking on a program to equip university and other seismic observatories all over the world with high-quality standard seismic equipment. With confidence in their judgment we may assume that high priorities are given to such countries as Mexico, Cuba (why not?), Norway, Turkey, Pakistan, India, and Japan. Russia should be asked to show her good will by placing this same equipment in a number of her observatories and by accepting U. S.-British seismologists, and per-

haps qualified neutral ones (pitfalls here: some neutrals are more neutral than others) on the staff of these observatories with the understanding that they will see and study all recordings. We would admit an equal number of Russian seismologists under the same conditions to our observatories. Such an exchange offer will be hard to turn down for those who try to convince the world that they are the champions of peace. It would also help in breaking down the Iron Curtain, an objective advocated so well in Dr. Bethe's article in the *Atlantic Monthly*. We could negotiate with the Russians on a reduction of the number of Geneva stations within the U.S.S.R. in exchange for such mutual control of observatories by a seismic observation corps for atomic peace.

(4) In our own country a few more Geneva-type stations, like the Wichita Mountains Seismic Stations, should be built, but not all situated as favorably. Their activity should then be directed especially at the detection of cheating, even if this would cause our scientists to be chided again by their Russian colleagues for spending time on methods of cheating (*Atlantic Monthly* August 1960, p. 46). This may be done by the separate registration on tape, and later compositing, of a muffled nuclear explosion and several attempts at jamming the detection by smaller preceding explosions (either chemical or nuclear); by blizzard and storm noises; by rumbling tanks, trains, and trucks; by highway and quarry blasts. Theoretical studies on the refinements in analysis that are likely to yield a factor of a few in detection should be tied to this work.

(5) Basic research for a break-through to advance detection techniques by the needed factor in excess of one hundred should be limited to one or two "high-pressure" centers under the direction of top talent. The chances are small but, as the area of a delta-function, the product with the calamity of nuclear warfare remains finite. "Low-pressure" research at a large number of institutions is still less likely to lead to the needed break-through; it should be coordinated with the practical work mentioned in the preceding paragraph. Some way should be found to stop research projects when the reports show errors in logic, lack of scientific care, or lack of concern with reasonable progress.

(6) We should be extremely circumspect about a unilateral commitment of substantial capital and man power of the free world in a multibillion-dollar chess game with a crafty opponent who is likely to use this program to keep others from working on small-yield weapons while proceeding, himself, as he chooses. Any concessions he makes may be booby-trapped, perhaps may even have to be so in order to obtain the consent of the right-wing Iron Curtain diehards and warlords for any cooperation with the West suggested by the real forces of peace behind the Iron Curtain. The consequences of losing such a cold war chess game are ridicule in the eyes of the world, resentment of the needy peoples over billions appropriated for a seismic Maginot line of uncertain value in the face of their certain misery, frustration, and demoralization among thousands of our vitally needed technicians, engineers, and scientists. Such are the stakes in the battle of wits with the Marxist dictators. The Geneva control project must be kept down to a size where it will neither offend the underdeveloped nations nor create at home a Maginot-line mentality to take the place of the outgoing spirit which alone can keep the nations of the world from being lured into submitting to police state regimes.

Research must advance detection by a factor in excess of one hundred, a break-through on which we cannot reasonably count, before a multi-billion-dollar project of DEW-line magnitude would appear to be justified.

GEOPHYSICS AND CONGRESS

THE HONORABLE GEORGE P. MILLER†

I approach the task of addressing this distinguished group of Geophysicists with some trepidation. I am a layman, and I do not want to impart in any way that what I say can be taken in a technical sense.

I salute you and I honor you and respect you for the great contribution you have made in the field of science. Thinking people in the world are now coming to know that, if we are going to survive on this planet, we must study it and know it. We must go into the air above, the depths of the ocean, and probe beneath the Earth's crust to find her locked-in secrets.

As Chairman of the Permanent Sub-Committee on Oceanography of the House Committee on Merchant Marine and Fisheries, as well as Ranking Majority Member of the House Committee on Science and Astronautics, I feel that my remarks and personal conclusions with respect to earth sciences should be of interest to you.

One often asks the question: What are the boundaries of our thinking with respect to the study of the earth? I feel that, if one is to consider the question, it is inevitable that the conclusion is reached that the earth, the atmosphere, and outer space are as inseparable as the fore and aft quarter of a domestic animal.

We must concern ourselves with the entire ensemble as well as its various component parts. This truism creates problems of national importance especially in the field of properly and adequately funding the prosecution of our search for knowledge. Further, the determination of the natural laws governing the interrelation of the bits and pieces of our ensemble requires long-range thinking, planning and the scientific intuition of masterminds. We must take the lead in all phases of the problem for our very survival!

Let us, for a moment, contrast the study of the atmosphere and outer space with that of the earth and its interior. In both instances I prefer to regard these as studies of environments which have mutual interdependence. To formulate the laws governing the known and yet to be found phenomena which characterize both, it is necessary to employ all possible scientific disciplines separately and in combination. In addition, the ability to measure and thus be able to describe the present state and forecast the future state of both environmental divisions has the common requirement of a vehicle to carry the equipage to the particular spatial location desired. Herein the similarity stops. I shall attempt to point out some of the differences.

THE ATMOSPHERE AND OUTER SPACE

The vehicle must manifestly leave the surface of the earth and needless to say the expense of each vehicle is fantastic. Before I left Washington I requested my staff to ascertain the amount of money appropriated by the Congress for the study of lunar geophysics. The amounts in millions of dollars are as follows:

Fiscal 1959	31.9
Fiscal 1960	37.8
Fiscal 1961	60.0

It should be pointed out that the 1962 appropriation has not yet been enacted. However, some wag remarked that the funding seems to be increasing logarithmically. Manifestly the motivation for this enormous expenditure is twofold in nature. First, to attain a national posture of world leadership in scientific exploration; second, to ensure our capability in the area of national defense. Programs of this nature by their very magnitude require Federal financing.

The establishment of nationwide tracking stations, computing centers, and test facilities is a governmental function. Private industry, universities, and other scientific institutions must be integrated into the program to achieve the maximum results in the least time.

No group possessing the scientific capability should regard itself as too small to make a contribution!

Again, another important consideration that enhances such programs is the public interest. These programs have no historical length. They are new, unusual, and often fantastic in the minds of the American citizens. The competition from the Russians is always apparent to even the youngest member of our society. He has seen Sputnik. My grandson can buy a toy rocket at the corner store propelled by a jet of water under pressure which will attain an altitude of

* Address presented at the 14th Annual Midwestern Meeting, Oklahoma City, April 10, 1961.

† Member of United States Congress representing the Eighth Congressional District of California.

several hundred feet. He then relives, in actuality, the dreams of Jules Verne.

To summarize, the geophysical programs in the atmosphere and outer space have the following attributes: It is possible to put a vehicle at any point in space, track it and receive information from its sensors by telemetry for analysis; the cost is enormous; the popular appeal is universal; and as yet material benefits are unforeseeable.

THE EARTH AND ITS INTERIOR

Somehow, to me, although I have flown several times in jet fighters, the mystery of our daily contact with the crustal environment that we are born on, grow to maturity, and eventually meet our Maker, has always been fascinating. Perhaps it is because we are so close to the earth that it loses somewhat the feeling of the spectacular that space gives us. If we were practical in our thinking and realized that Mother Earth is responsible for all that we experience in our lives, in fact our very life alone, we should become more enamoured with seeking relationships between effect and cause.

With respect to vehicles, on the Continents we have only a two-dimensional capability if one excludes the drilling of holes at a point on the surface. The cost of the vehicle is less than the cost of the instrumentation. On the sea we have the possibility of three-dimensional vehicles with the modern submarine and I am happy to see that the U. S. Navy has an oceanographic submarine the USS *Archerfish*. This, of course, is only a start.

The other difficulty we face, as you gentlemen well know, is that even on the crust we have such extremely complicated relationships between stress and strain, the albedo of the earth, the production of heat within the earth, and the geomagnetic and gravity effects that simple causal relationships are at best understood by an extremely approximate model.

Adding to this the necessity of indirect measurements of effects through seismic, gravity, magnetic, and radiation means, the problem presented by this phase of geophysics is much more difficult than that of the geophysics of the atmosphere.

That which is of much concern to me is that we do not as yet have in being an integrated program of investigation of the geophysics of the earth. We have, of course, the seismic networks, the gravity and magnetic surveys that your Society has been instrumental in developing. Tied in with this are the surveys and investigations by the U. S. Navy, the Coast and Geodetic Survey and certain non-profit institutions with respect to the oceans. All of these have been spotty in nature. True, the geophysical industry had produced marked material benefits to mankind, but I feel as of now the surface has only been scratched.

I very definitely feel that we must have an integrated national program of geophysical research to the end that we can understand the crustal phenomena around us as well as examine from all the data possible the structure of the interior of the earth.

Further, we have by our close association with the earth extreme difficulty in sustaining and, in fact, creating interest in this part of earth sciences. A friend of mine once said: "It is easy to popularize a rocket flight to the Moon, but how can one sell an earthquake?"

In conclusion, I should like to say a few words about the geophysical industry and the Congress.

If the Congress does not know of the capabilities of your industry, you should show aggressiveness and tell the Congress of your capabilities.

Your industry certainly has the ability to be a vital factor in the surveys of the oceans of the world. Tell us about it!

Your industry has developed an outstanding series of developments in instrumentation. Tell us about it!

You gentlemen are motivated by a necessity of making a profit. Don't be ashamed of this! This is what has made America. Why not give the non-profit institutions a little competition?

Gentlemen, I thank you.

REVIEWS

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Theory of Detonation, Ia. B. Zeldovich and A. S. Kompaneets, Academic Press, New York, 1960, 284 pp., $10.00.

This is an excellent book—the best available on the theory of detonation. Through the years this subject has been a challenge to and has attracted the attention of many able theoreticians including mathematicians, physicists, and chemists. Zeldovich is the first of these to write a book presenting a broad discussion of the subject. Although the treatment is rigorous and based on a sound understanding of the dynamics involved, the book is by no means for experts only. The authors succeed very well in making the physical meaning clear at all times. Basic points are emphasized and are often approached from several points of view. Numerical examples are used to give the reader a quantitative picture of the physical processes.

The coverage is broad but not exhaustive. The first chapter (61 pages), "The Elements of Gas Dynamics," is an excellent discussion of this prerequisite subject, including shock waves, the method of characteristics, and applications on the one hand to ideal gases and on the other to the special case where the adiabatic exponent, K, equals three, is useful in the discussion of the products of the detonation of solid or liquid explosives. Chapters II and III, comprising over half the book, discuss *The Detonation Regime and Lossless Combustion* and *Theory of Detonation with Losses and the Limits of Detonation*. Although some of the theory is of a general nature, most of these chapters deal specifically with gaseous detonations. The final two chapters, the *Detonation of Condensed Explosives* and *Motion of the Detonation Products*, comprise some 79 pages devoted almost completely to solid and liquid explosives. The discussion of the equation of state of the detonation products is illuminating.

In spite of the general excellence of the book, there are some minor shortcomings. Much work done outside Russia is ignored; in particular, there are very few references to the literature of other countries after 1940. The strong performance of the Russians in this field in the decade following the war not only keeps this from being a major shortcoming but emphasizes the value of the book in making this work accessible to us. It must also be noted that the book is not quite up to date, being a translation of the Russian edition published in 1955. The work of Deal and others concerning the experimental determination of the pressure-volume curves of the products of detonation of high explosives and the extensive experimental work in this country and in Russia on the shock compression of solids have been noteworthy contributions since then.

The geophysicist interested in the use of explosives

may have more need for a book which contains more information on the practical uses of high explosives. It is unfortunate, but true, that most of the books dealing with high explosives contain unsound descriptions of the basic dynamical behavior of the system, sometimes bordering on the nonsensical. For those who must use such books for the needed practical data, the reading of the book by Zeldovich and Kompaneets should prove a corrective and a tonic.

GEORGE R. COWAN
E. I. Du Pont de Nemours Company
Gibbstown, New Jersey

Methods and Techniques in Geophysics (Vol. 1), edited by S. K. Runcorn, Interscience Publishers, Inc., New York, 1960, ix+374 pp., $10.00.

Although elementary books and review papers have been published on the theoretical and interpretive results of geophysical data, no comparable publication is available on the methods and techniques of obtaining observational data. This book seeks to correct these shortcomings by presenting ten well-organized and edited articles on the geophysics of the earth. Emphasis is made on physical principles, method of measurement, and the shortcomings or limitations of the technique. The book will prove of inestimable value to the experimental geophysicist engaged in research and to the geologist interested in methods and limitations of a particular geophysical technique. Also, there is a large and apparently complete bibliography at the conclusion of each chapter.

Chapters one and two discuss the temperature gradient and heat flow over land. These chapters are highly recommended, particularly for the discussion on instrumentation, field methods, and shortcomings of the method.

Chapter three is a review of borehole surveying. This is a good review of the method but lacks an adequate discussion on limitations.

Chapter four, dealing with the method of measurement of the geomagnetic elements, is well done and fills a real need for practicing geophysicists. The measurements involve the torque, induction, saturable core, Hall effect, magnetostrictive, and proton-precession methods.

Chapter five, a discussion on paleomagnetic measurements, is also superbly done. The first section on natural remanent magnetization describes the principles of the astatic and rock-generator magnetometer. The second section includes a discussion on susceptibility measurement, saturation magnetization methods, apparatus for the study of temperature effects, and demagnetization by alternating magnetic fields.

Chapter six describes measurements of gravity at sea, the Vening-Meinesz pendulum, the Graf, La Coste, and Vibrating-string gravity meters. A theoretical explanation of the gravity meter stabilized in the vertical direction and also one suspended in gimbals is presented.

Chapter seven gives a rather complete description of the theory and use of the pendulum seismograph.

Chapter eight reviews the general subject of earth currents, with particular emphasis on theory. Unlike the preceding chapters, the method and techniques of measurement leave much to be desired. It would be well to include a more complete description of surveying methods and their limitations.

Chapter nine on the properties of rocks under high pressure and temperature is much too abbreviated. It appeared, to this reviewer at any rate, that this important chapter was hastily prepared and that the method of measurement of physical properties under high pressures and temperatures deserves a more complete description than that presented here.

Chapter ten gives an excellent account of astronomical techniques to locate the position of the pole and a discussion of its secular motion.

ISIDORE ZIETZ
U. S. Geological Survey
Washington, D. C.

The Sea Off Southern California, K. O. Emery, John Wiley & Sons, Inc., New York and London, 1960, xi+366 pp., $12.50.

The purpose of this book, as stated by the author, is to bring together in a single volume much of the material contained in the more than 2,500 scientific articles which have been published during the last 120 years on various aspects of the sea floor, the water, and the marine life off Southern California. Such an interpretation of individual contributions is hoped to prove helpful to other investigators working in this region and a guide to what may be expected in other less well-known regions of the sea floor.

The subtitle of the book, *A Modern Habitat of Petroleum*, indicates an important secondary objective of the author: to describe the basic environmental factors of the region; to relate them to each other and, whenever possible, to the general problem of origin and accumulation of petroleum, one of the most important resources of the region.

Dr. Emery is well qualified to winnow from the vast prior publication of material suitable for his purposes since he has done research since 1935 in this field in this very area, as well as having conducted field studies at Bikini, Guam, Alaska, Israel, in the Persian Gulf, and the Hawaiian Islands. Several of the more important scientific papers previously published in the area are under his authorship or co-authorship. He has not only been active personally in the field investigations but has been in close personal touch with others, including petroleum explorationists, working in this area and on oceanographic problems all over the world. This book

has been a long time in preparation, has been carefully brought up-to-date to the very moment of publication, and should stand as a valuable reference for a long time just as it stands. It may be hoped, however, that the author will issue revised editions occasionally to keep abreast of future investigations in the area.

It would appear that Dr. Emery has succeeded admirably in his objectives in the specialized field of oceanography. Your reviewer is only qualified to state that the author presents a very coherent, well-organized, and apparently complete picture of the oceanography, of the "Continental Borderland" off the Southern California coast and relates it in a most meaningful manner to world-wide oceanography. Though the book is packed with factual data collected from many sources, the difficult job of integration has been done so carefully, the organization is so well planned, and the inferences and conclusions so cogently woven into the factual data that the book reads almost like an adventure. As such it may be viewed, a scientific adventure of many men logged by an imaginative leading member of the 120 year expedition.

The book is beautifully and appropriately illustrated by 248 figures, including 63 figures containing one or more excellent photographs, and 31 tables of data. The work is scholarly and highly professional. The author points out some of the controversies in interpretation as they stand today. In such a dynamic field he may be excused for perhaps omitting mention of others.

The scope of the book may be indicated in somewhat greater detail by a listing of the several "sections" of the book and the emphasis roughly indicated by the number of subsections and pages devoted to each section, though it must be agreed that each section should not be expected to support an equal number of pages.

Section	Subsections	Pages
Physiography	9	61
Lithology	5	16
Structure	7	20
Water	5	42
Life	6	41
Sediments	8	116
Economic Aspects	4	33
References	—	22
Author Index	—	8
Subject Index	—	7

There is hardly a subsection which will not be of interest to the petroleum geologist concerned with the origin and accumulation of oil. Perhaps, however, one might single out the section entitled "Sediments," culminating in a subsection entitled "Origin of Petroleum," as containing the most food for thought for such readers. This longest section of the book is, to be sure, rather specific as to this particular area; but its lessons no doubt will suggest parallel lines of thought applicable to other environments to stimulate readers with this special interest.

Much of the book is not directly applicable to exploration geophysics; but, in the sense that an effective exploration geophysicist must understand the environment affecting his data and his interpretations and the nonstructural factors economically important in oil exploration, the entire book is a "must" for the well-rounded man in this field. However, for the geophysicist exploring for oil offshore, the Section on "Structure" with its subsections; "Faults Inferred from Topography," "Seismicity," "Geomagnetism," "Gravity," "Seismic Surveys," "Minor Structures," and "General Structural History"; is of direct and basic interest. Though one finishes this Section with a sense of regret at its shortness, it is meaty and to the point and includes specific illustrations which a marine geophysicist, especially one concerned with the area described, cannot afford to miss.

Other portions of the book are of considerable practical importance to the California marine geophysicist and, by analogy, to the marine geophysicist working anywhere in the world. The Sections on Physiography and Lithology are a great help in programming geophysical exploration at sea in this area and in the interpretation of the resulting data. Seismic data quality is particularly sensitive to the topography and composition of the sea floor. These factors must also be taken into consideration in the interpretation of magnetic and gravitational surveys.

A pocketed two-color 30 inch×30 inch map of the submarine and adjacent land topography at a scale of 1:500,000 is a particularly valuable addition to this book. Studied in conjunction with the book, this map is not only a vital guide to exploration programming and interpretation in this area but should illustrate how similar maps may be valuable in other areas where they may be available.

It is believed that all serious exploration geophysicists, and even more especially geologists, will find this book a unique and valuable reference and will, moreover, thoroughly enjoy its reading.

CURTIS H. JOHNSON
Geophysical Consultant
Los Angeles, California

The Microstructure and Macrostructure of Elastic Waves, B. N. Ivakin, American Geophysical Union, New York, 1960, viii+113 pp., $6.00.

The paper reviewed by this report was originally published in the Russian language. The translation to English has not appreciably changed the views or the general approach of the original author to the subject under discussion. This fidelity in translation is attributable to two important factors: (1) the excellence and experience of the translator, and (2) the fact that a large percentage

of the work is mathematics, and thus, this portion of the paper essentially remains fixed during translation.

Before attempting to review the paper, the terms used in the title of the paper need some explanation for those who are not familiar with the subject of wave propagation. The author defines microstructure of elastic waves in nonhomogeneous media, by their velocity of propagation, amplitude variations, and other wave characteristics. All of these items may be measured or observed along baselines which are small or comparable with the wave lengths observed in the media. Macrostructure of waves in nonhomogeneous media represents the elastic wave characteristics that may be measured or observed along baselines longer, or appreciably longer, than the wave lengths observed in the media.

The author makes generous use of transmission line theory of electrical four-pole networks for an analog treatment of the problems. The nonhomogeneous mechanical transmission line (an acoustical waveguide) is reduced to an electric analog representing a nonuniform electrical transmission line. Details supporting the theory of electromechanical analogs are not given; however, adequate references are cited so that an interested reader may readily investigate the computational representation employed. The computational treatment is held to only one class of single-dimensional plane wave problems dealing with nonhomogeneous, continuous media.

An interesting concept of a differential propagation constant of a nonhomogeneous waveguide is introduced as an aid in solving the wave problems. The use of this propagation constant serves to avoid establishing the internal wave properties of the nonuniform transmission lines used with analog treatment. Other benefits from this concept are (1) that it makes possible the study of the internal wave characteristics of the waveguide over so-called infinitesimally short baselines, and (2) it greatly simplifies the stating of the problem in a single-dimensional medium with continuously varying elastic characteristics and leads to the customary first-order differential equation.

Practically all solutions to the wave problems presented are left in the operational form which is convenient to study by the procedures of operational calculus. The solutions should be useful to anyone who desires to examine the transient behavior of oscillations in nonhomogeneous layered media. The solutions are supplemented by calculations and graphs for steady-state sinusoidal excitations.

Several cases of the distribution of nonhomogeneous media are considered: (1) two media with a single, common, interior boundary; (2) three media with two interior boundaries; and (3) layered media having an arbitrary number of interior boundaries. Only plane waves propagating in the direction normal to the layer boundaries are treated. No case of oblique incident angles of the ray paths is considered.

Rules controlling the variations of the phase-velocity of elastic waves measured over distances less than their wave lengths are determined. The rules given embrace functions of the characteristic wave impedance ratio at the interior boundaries, coordinate of a single-dimension of the nonhomogeneous medium, and the frequency of the wave. Variations in the amplitude of the wave are also considered in the study. The frequency dependence on phase-velocity (dispersion) over distances larger than the wave lengths of the propagating elastic waves are investigated for the three mentioned cases of distribution of nonhomogeneous media.

The author makes the observation that the difficulties are great and the problem laborious in considering the case where the elastic properties vary continuously in the propagating media.

In general, this paper would be of little interest to the practical field type of geophysicist because of its theoretical and simplified approach to a rather complicated problem. The practical seismologist is more interested in information on the case where the angle of incidence of the waves is less than 90 degrees at the interior boundaries of the propagating media than on the situation represented by perpendicular incidence. Obviously the author chose normal incidence of the ray paths, plane waves, and one-dimensional media, to simplify the mathematical analysis.

On the other hand, seismologists engaged in the study of the effects of interior boundaries of the media on elastic wave propagation will find the paper both instructive and suggestive. Those scientists working with seismic logging of boreholes penetrating layered media may also find the information presented by this paper interesting and useful. It is the presumption of the reviewer that the technique outlined by the paper may be extended to the more general and more complicated cases experienced in nature and to the practical application of exploration seismology.

From the point of view of American standards for technical articles, the reviewer found the paper to lack some coherence. However, the paper certainly demonstrates a scholarly approach to a complicated analysis. It contains a valuable list of 30 references.

The book deserves space in every library used by research workers in seismology.

JOSHUA L. SOSKE
Department of Geophysics
Stanford University

Hydrodynamics of Oceans and Atmospheres, Carl Eckart, Pergamon Press, New York and London, 1960, xi+290 pp., $9.00.

This book provides a systematic account of the motions of a stratified compressible fluid. The effects of viscosity and turbulence are not included. In the author's words " . . . in geophysics, there are two Reynolds numbers. The first is the ordinary one $R = VL/\nu$, V being a

typical velocity, L a typical length, and ν the kinematic viscosity. The other is $R_\sigma = NL^2/\nu$, N being the Väisälä-Brunt frequency. In laboratory experiments, $R_\sigma \ll R$, and the latter will dominate the phenomena. For large, or moderately large-scale phenomena in the geophysical fluids, $R_\sigma \gg R$, and the former will dominate. Consequently it is most improbable that the results of laboratory investigations of turbulence will have much relevance to turbulence in the air or oceans."

Beginning with the basic equations and the perturbation equations, the author goes on to the steady motions, field equations, and the earth's atmosphere, oceans, and lakes. Chapters VI and VII deal with general theorems concerning field equations (expansion theorems) and the formulation of the major mathematical problems. The next two chapters analyze the isothermal atmosphere (plane level surfaces with and without rotation) followed by the oceanic case with constant coefficients. The next three chapters are devoted to ray theory with applications to the thermocline and thermosphere, followed by two chapters on the general theory of the residual equations (including their canonical form and theorems on the phase paths) and applications. The final two chapters treat the wave equation for a spherical surface and spherical level surfaces with rotation. An appendix on Mercator coordinates completes the book.

An especially appealing feature is the introduction to each chapter which is not merely a summary, but sets out clearly the limitations of the techniques as they are developed. The book can be recommended not only to the meteorologist and oceanographer requiring a knowledge of analytical techniques of mathematical physics, but to the theoretical physicist interested in applications of nonclassical hydrodynamics.

H. KAUFMAN
McGill University
Montreal, Canada

An Introduction to Statistical Communication Theory, David Middleton, McGraw-Hill Book Company, Inc., New York, 1960, xix+1140 pp., $25.00.

Middleton's book is an important addition to McGraw-Hill's distinguished *International Series in Pure and Applied Physics*. Written in a style which will appeal to both engineers and physicists, the book summarizes much of our present day knowledge in this field and in addition presents new developments which have not been previously published.

In fairness to the prospective reader it ought to be stated, however, that this book is not, in fact, an "introduction," as the term is usually understood. It is, rather, an advanced level, scholarly compendium, moving in an encyclopedic tempo and drawing very heavily on the assumed previous knowledge of the reader, which, in addition to several advanced courses in mathematics, should also include the knowledge of statistical communication theory as it is usually presented in the more elementary textbooks.

The table of contents omits nothing that is relevant to this field, but the treatment of each topic is, of necessity, compendious. For example, *Information Theory* is covered in fewer than forty pages. Realizing this limitation, the author has supplied over 500 references (some as late as 1958) and this enables him to direct the interested reader to either the original sources or to some fuller treatment of a particular topic. Perhaps this is the sense in which the author uses the word "introduction" in the title of his book.

The subject matter is divided into four parts. Part I (330 pp.) deals with statistical ensembles, sampling and interpolation, nonlinear systems and their effect on signals and noise, information theory, etc. Part II (173 pp.) includes Gaussian processes; discrete random walk and the transition to the diffusion equation; the equations of Langevin, Fokker-Planck, and Boltzmann (of particular interest to physicists); and a chapter on physical sources of noise. Part III (260 pp.) is devoted to various modulation systems, prediction, and filtering. Part IV (295 pp.), containing much previously unpublished material, is concerned with decision procedures as applied to signal detection and extraction.

Middleton's book is not recommended for anyone who has only a modest acquaintance with this subject. On the other hand, it is an indispensable source book for the serious professional who is engaged in research work involving the statistical methodology of communication theory.

Finally, for the benefit of all those readers whose curiosity may be aroused by the two lines printed in Sanskrit (author's preface), this reviewer made an appointment with Dr. Judith Tyberg (a Sanskrit scholar) who graciously and without hesitation gave this translation: "Destroyed is my delusion, I have regained memory through Thy grace, Oh Infallible One.—I am firm in my beliefs, dispelled are my doubts, I will act according to Thy word."

This reviewer doesn't wish to comment on the relevance of this quotation to the rest of the text. He would rather leave it to the interested reader as a refreshing exercise in the art of cross-correlation technique.

MARK HOLZMAN
Western Geophysical Company of America
Los Angeles, California

PUBLICATIONS RECEIVED

BOOKS

A Hole in the Bottom of the Sea, by Willard Bascom, Doubleday & Co., Inc., $4.95.

On Thermonuclear War, by Herman Kahn, Princeton University Press, $10.00.

Statistical Theory and Methodology in Science and Engineering, by K. A. Brownlee, John Wiley & Sons, Inc., $16.75.

The World of Geology, by L. Don and Florence J. Leet, McGraw-Hill, $4.25.

PERIODICALS

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Chronique de l'U.G.G.I., n. 34 (March, 1961).

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Erdol und Kohle, v. 14, nos. 2, 3, & 4 (Feb., March, & April, 1961).

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Geophysical Digest, v. 8, nos. 3 & 4 (July & Oct., 1960).

Geophysical Prospecting, v. 9, n. 1 (March, 1961).

Gerlands Beitrage zur Geophysik, v. 70, n. 1 (1961).

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Journal of Geophysical Research, v. 66, nos. 3 & 4 (March & April, 1961).

The Mines Magazine, v. LI, nos. 4 & 5 (April & May, 1961).

Mining Engineering, v. 13, n. 4 (April, 1961).

Nachrichten aus dem Karten -und Vermessungswesen, v. 1, n. 18 (1960).

Physics Today, v. 14, nos. 4 & 5 (April & May, 1961).

Proceedings of the Cambridge Philosophical Society, v. 57, n. 2 (April, 1961).

Quarterly Journal of the Geological Society of London, v. 117, part 465 (March, 1961).

Rocznik, v. 30, n. 3 (1960).

The Science Reports of the Tohoku University, v. 12, n. 1 (Sept., 1960).

Transactions American Geophysical Union, v. 42, n. 1 (March, 1961).

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,971,151. R. C. Mierendorf and C. F. Meyer. Iss. 2/7/61. App. 2/14/58. Assign. Square D Co.

Metal Detectors. A search unit for a metal detector having an axial ferromagnetic rod with a central pick-up coil and energizing coils at each end and a cylindrical outer sleeve of magnetic material, the assembly being potted in a moldable plastic material.

GEOCHEMICAL PROSPECTING

See patents 2,967,932; 2,968,761; 2,972,251; and 2,973,471 listed under WELL LOGGING and patent 2,968,762 listed under MISCELLANEOUS.

GRAVIMETRIC PROSPECTING

U. S. No. 2,968,952. J. J. Stalder. Iss. 1/24/61. App. 9/21/59. Assign. U.S.A.

Force Measurement System. A vehicle accelerometer in which a proof mass is mounted on a pivoted arm whose motion is counterbalanced by electrostatic forces between charged plates whose potential difference is controlled from a capacitance-type displacement detector.

MAGNETIC PROSPECTING

U. S. No. 2,966,853. E. S. Gilfillan, Jr. and S. J. Sindeband. Iss. 1/3/61. App. 10/27/41.

Buoyant Mine with Gradiometer. A device for detecting magnetic gradients having two axially aligned high permeability rods with adjustable magnetic fingers extending angularly from the ends of the rods, the fingers being adjusted so that rotation of the system in a uniform field produces no output signal from coils wound on the rods and connected in opposition.

U. S. No. 2,972,104. R. C. Ward. Iss. 2/14/61. App. 5/11/59. Assign. Space Technology Laboratories, Inc.

Magnetic Field Responsive Apparatus. A magnetometer having two microwave signal generators that excite cavity resonators one of which contains a ferrite rod that is mechanically rotated, the modulation of the difference frequency of the resonators being observed.

U. S. No. 2,972,105. R. N. Ghose. Iss. 2/14/61. App. 5/11/59. Assign. Space Technology Laboratories, Inc.

Magnetic Field Responsive Apparatus. A magnetometer having two microwave signal generators that excite cavity resonators one of which contains a ferrite that is affected by the ambient magnetic field, the difference in resonant frequencies being observed.

RADIOACTIVITY PROSPECTING

U. S. No. 2,967,935. J. D. Cook. Iss. 1/10/61. App. 5/6/57 and 3/26/58. Assign. North American Philips Co., Inc.

Scintillation Detector. A radiation detector having a box with a phosphor on one inside surface and an opening for a phototube on the opposite side with the opening surrounded by a short thin right-circular cylinder having internal and external light reflecting surfaces.

See also numerous patents relating to radioactivity well logging listed under WELL LOGGING.

SEISMIC PROSPECTING

U. S. No. 2,966,855. J. F. Barco. Iss. 1/3/61. App. 3/20/58. Assign. Airmite-Midwest Inc.

Explosive-Containing Bag Used in Blasting. A bag for loading granular ammonium nitrate in a borehole, the bag having an outwardly gaping pleat closed by a frangible strip with a rip cord so that after the bag is loaded in the borehole the rip cord may be pulled to allow the bag to expand into intimate contact with the borehole wall.

U. S. No. 2,966,953. K. O. Heintz. Iss. 1/3/61. App. 11/14/55. Assign. Jersey Production Research Co.

Apparatus for Presenting Seismic Data. A system of portraying seismic data in which each positive wave excites a damped shock-excited high-frequency oscillator whose output is recorded, the length of time of the oscillation depending on the amplitude of the seismic wave and the sudden onset of the oscillation indicating the reception instant of the seismic wave.

U. S. No. 2,967,291. C. H. Carlisle, F. L. Chalmers, and J. A. Smith. Iss. 1/3/61. App. 6/7/55. Assign. Jersey Production Research Co.

* Gulf Oil Corporation, Patent Department.

Automatic Plotter. A seismic cross-section plotter having two drums with the geophone signals magnetically recorded on the first drum and successive recordings reproduced and rerecorded on an electrosensitive medium on the second drum, the magnetic heads being movable to effect corrections.

U. S. No. 2,967,292. E. Eisner. Iss. 1/3/61. App. 9/6/55. Assign. Texaco Inc.

Data Processing Method and Apparatus. A digital seismic recording system in which the geophone signal is applied to a voltage divider with taps controlled by gate circuits, and the signal to be recorded is compared with a reference signal by a synchronous counter whose digital indications are magnetically recorded on a multitrack drum, the amplitude of the digitalized output also actuating the voltage divider gates to control the amplitude of the digitalized signal, and a digital signal that indicates which gate is operative also being recorded on the magnetic drum.

U. S. No. 2.967,956. A. I. Dranetz and H. J. Cullin. Iss. 1/10/61. App. 4/19/55. Assign. Gulton Industries, Inc.

Transducer. An underwater sound transducer using a disk of piezoelectric material exposed to the sound pressure on one side and backed on the other side by a mass that contacts the disk only at its center so that flexure of the disk takes place.

U. S. No. 2,968,022. R. R. Unterberger. Iss. 1/10/61. App. 10/11/54. Assign. California Research Corp.

Seismic Signal Digitalization Method and Apparatus. A pulse digitalizing system in which the pulses are sampled to obtain the onset time and used to gate a fast pulser whose pulses are counted during the sampling interval.

U. S. No. 2,970,479. A. Wikstrom. Iss. 2/7/61. App. 2/25/58. Assign. AVCO Manufacturing Corp.

Wide Range Accelerometer. A taut wire accelerometer having an inertia mass on one end and a second mass surrounding the wire so as to produce a vibration node at its location, the natural frequency of the wire being observed.

U. S. No. 2,970,876. H. H. Moody. Iss. 2/7/61. App. 6/8/59. Assign. Continental Oil Co.

Direction Indicator for Seismic Field Setups. A system for recording the direction of a seismometer spread having a circular d-c potentiometer whose case is manually oriented with respect to a magnetic compass and whose sliding contact has a pointer manually oriented in the direction of the spread, the potential between the pointer and one end of the potentiometer being recorded.

U. S. No. 2,972,733. J. F. Bucy, Jr. Iss. 2/21/61. App. 7/19/55. Assign. Texas Instruments, Inc.

Method and Apparatus for Analyzing Data. An electronic seismic reflection picker in which each seismic trace is converted from analog to digital form, differentiated, and used to trigger a gating circuit, the impulses from the respective gating circuits being fed to a coincidence circuit that indicates the number of traces having coincident pulses at a particular time.

See also patent 2,970,666 listed under WELL LOGGING.

WELL LOGGING

U. S. No. 2,967,241. J. T. Dewan and W. D. Lunn. Iss. 1/3/61. App. 1/16/56. Assign. Schlumberger Well Surveying Corp.

Well Logging Apparatus. A radioactivity logging apparatus having a source and two cylindrical axially aligned detectors spaced different distances above the source, each detector having a central electrode and with the connecting lead to the lower detector passing through a small cylindrical shield in the upper detector.

U. S. No. 2,967,245. S. Soloway. Iss. 1/3/61. App. 3/8/54. Assign. Schlumberger Well Surveying Corp.

Neutron Source for Well Logging Apparatus. A sealed borehole neutron source having a source of deuterium gas and an ionizing discharge and electrodes to accelerate ions to a target containing tritium, control being provided by the potential on a deflecting electrode that deflects the beam off the target, or by control of the source of gas.

U. S. No. 2,967,272. H. Janssen. Iss. 1/3/61. App. 3/27/57. Assign. PGAC Development Co.

Electrical Well Logging. An a-c electric logging system using a current electrode with screen electrodes whose current is controlled by the amplified output of a transformer connected between the current electrode and one screen electrode, and the potential difference between the current electrode and a remote reference electrode is recorded as a measure of formation resistivity.

U. S. No. 2,967,932. R. B. Edwards and E. H. Koepf. Iss. 1/10/61. App. 1/15/57. Assign. Core Laboratories, Inc.

Gas Detecting and Analyzing Methods and Apparatus. A mud logging system in which gas from the mud is analyzed by means of a linear-type electrostatic mass separator that is automatically set on hydrocarbon ion peaks and the ratio of component ion currents recorded.

U. S. No. 2,967,933. S. A. Scherbatskoy. Iss. 1/10/61. App. 11/7/55.

Dip Determination. A radioactivity logging apparatus having a neutron source and a plurality of directional

gamma-ray detectors in a transverse plane each connected to a threshold network and rate meter and separately recorded against depth on a common chart.

U. S. No. 2,967,937. A. S. McKay. Iss. 1/10/61. App. 12/16/55. Assign. Texaco Inc.

Method and Apparatus for Measuring Thickness. A system for determining the thickness of pipe in a borehole having a source of fast neutrons and a detector of thermal neutrons in the sonde, the fast neutrons penetrating the pipe and moderated by the water in the formations and returning to the detector with the intensity depending on pipe thickness.

U. S. No. 2,967,942. G. E. Davis and E. J. DiIanni. Iss. 1/10/61. App. 6/2/59.

Apparatus for Testing Radiation Detection Devices. A device for mounting radioactivity detectors and surrounding them with equally spaced individually rotatable radioactive sources in the form of strips parallel to the axis of the detector so that the directional sensitivity of the detector can be determined.

U. S. No. 2,967,994. G. Peterson. Iss. 1/10/61. App. 3/25/57. Assign. Well Surveys, Inc.

Casing Joint Locator. A magnetic casing joint locator having an axial permanent magnet with axial magnetically soft pole pieces at each end wound with coils connected differentially.

U. S. No. 2,968,724. C. M. Clark. Iss. 1/17/61. App. 6/28/57. Assign. California Research Corp.

Pulse Height Analyzer. A radioactivity well logging system in which pulses are recorded on the storage surface of a c-r tube with rotating magnetic deflecting field and with the radial distance of the stored pulse proportional to the pulse energy, the storage surface being read out and erased at regular depth intervals or upon completion of the survey.

U. S. No. 2,968,728. H. C. Eberline. Iss. 1/17/61. App. 11/18/55. Assign. Eberline Instrument Division of Reynolds Electrical and Engineering Co., Inc.

Underground Exploration Apparatus. A circuit for a Geiger counter in a radioactivity logging sonde having the cable connected to one terminal of a low impedance transformer winding and the counter connected to the high impedance winding, the other terminals of the two windings being connected together and to ground through a condenser, with d-c supplied to the counter through the cable and the transformer windings.

U. S. No. 2,968,761. J. R. Zimmerman and J. O. Ely. Iss. 1/17/61. App. 5/20/54. Assign. Socony Mobil Oil Co., Inc.

Nuclear Relaxation Time Ratio Measurements. A nuclear magnetic resonance well logging system having in the sonde an axial permanent bar magnet above and below an exploring coil to which two r-f pulses are repeatedly supplied, and in which the ratio of transverse to longitudinal relaxation times for protons is measured.

U. S. No. 2,970,666. J. C. Smith. Iss. 2/7/61. App. 10/8/58. Assign. Jersey Production Research Co.

Apparatus for Calibrating Seismic Velocity Loggers. A velocity logging apparatus calibrating device having a bakelite tube containing an acoustic coupling fluid into which the logging sonde can be placed and with a loading sleeve clamped to the outside of the bakelite tube.

U. S. No. 2,971,091. J. D. Ball. Iss. 2/7/61. App. 10/7/57. Assign. Jersey Production Research Co.

Radioactivity Logging of Boreholes. A neutron-gamma logging system using a pulsed neutron source and a scintillation type gamma-ray detector with light from the scintillator transmitted through a polarizer and Kerr cell so that the detector can be switched on and off.

U. S. No. 2,971,092. J. A. Rickard. Iss. 2/7/61. App. 11/21/57. Assign. Jersey Production Research Co.

Radiation Well Logging. A neutron-gamma logging system in which interference of neutrons with the gamma-ray counting is reduced by using a detector having a scintillator that generates light only as a result of electrons traveling at a speed greater than the velocity of light in the scintillator.

U. S. No. 2,971,094. C. W. Tittle. Iss. 2/7/61. App. 12/27/56. Assign. Gulf Research & Development Co.

Well Logging. A radioactivity logging method to determine the degree of penetration of fluid into the formation by introducing a neutron-absorbing material into the well fluid and applying pressure to force it into the formations, irradiating the formations with fast neutrons and observing the resulting gamma and slow neutron radiation from the formation.

U. S. No. 2,971,178. C. E. Reesby. Iss. 2/7/61. App. 2/13/56. Assign. Welex, Inc.

Flexible Connector for Conductor Core Cable. A quickly releasable connector for a well-logging cable having an inner electrical separable plug that connects the conductors and contained in a ball and socket type housing with part of each member cut away so that they may be quickly separated when turned into a proper orientation.

U. S. No. 2,972,050. J. H. Allen. Iss. 2/14/61. App. 5/29/58. Assign. Phillips Petroleum Co.

Underground Storage. A system for determining the level of an interface between two liquids of different densities by having two tubing strings to below the interface, one having a radioactive source floating on the interface and the other carrying a vertically adjustable radioactivity detector indicating at the surface.

U. S. No. 2,972,052. L. D. Wann. Iss. 2/14/61. App. 12/6/55. Assign. Continental Oil Co.

Radioactive Logging Apparatus. A radioactivity logging sonde having guides that contact the borehole wall mechanically connected to the source and detector so as to vary the source detector spacing in order to maintain a constant ratio between source-detector distance and borehole diameter.

U. S. No. 2,972,101. L. deWitte. Iss. 2/14/61. App 6/28/55. Assign. Continental Oil Co.

Electric Well Logging. An electric logging system using a pair of current electrodes and a pair of potential electrodes with the distance between the pairs larger than the distance between members of each pair, the potential electrodes being connected through a subtraction circuit also connected to a distant reference electrode to observe the second differential of potential at the potential electrodes.

U. S. No. 2,972,193. E. T. Young. Iss. 2/21/61. App. 11/7/58. Assign. Sun Oil Co.

Bore-Hole Clinometer. An inclinometer having a tank of compressed air that serves to float on an air bearing a weighted sphere carrying a magnetic needle, the pressure of the air also acting to unclamp the sphere to permit it to orient itself and exhaustion of the air allowing the clamp to hold the sphere in position.

U. S. No. 2,972,251. E. F. N. Harper. Iss. 2/21/61. App. 3/29/57. Assign. Well Surveys, Inc.

Method and Apparatus for Infrared Detection of Subsurface Hydrocarbons. An infrared radiation well-logging system whose sonde has a number of vials containing samples of hydrocarbon material having an infrared resonance absorption band and whose presence is sought in the borehole wall, and a number of vials containing non-resonant materials, with thermocouple junctions in the vials used to measure the differential temperature between the resonant and non-resonant samples so as to detect characteristic emission from the borehole wall.

U. S. No. 2,972,679. R. L. Caldwell and R. F. Sippel. Iss. 2/21/61. App. 6/19/58. Assign. Socony Mobil Oil Co., Inc.

Methods of Determining the Dimensions of Underground Cavities. A method of locating an interface in an underground storage cavity by lowering through tubing a gamma-ray source and a spaced detector of scattered gamma rays and moving the assembly to detect a change in scattered intensity.

U. S. No. 2,972,682. A. S. McKay and R. C. Reynolds. Iss. 2/21/61. App. 8/10/56. Assign. Texaco Inc.

Radioactivity Well Logging. A radioactivity logging sonde having a source and scintillation-type detector separated by a shield and in which the source has a collimating slot and the scintillator as in an eccentric cylindrical shield that is thin on the same side of the sonde as the source slot which is pressed against the borehole wall by a spring.

U. S. No. 2,973,444. J. T. Dewan. Iss. 2/28/61. App. 4/9/52. Assign. Schlumberger Well Surveying Corp.

Neutron Source for Well Logging Apparatus. An accelerator-type D-T reaction neutron source having a sealed tube with an ionization-gauge type ion source in an axial magnetic field and electrodes for accelerating deuterium ions to a target containing tritium, the pressure in the tube being such that the mean free path of gas is of the order of the spacing between source and target.

U. S. No. 2,973,471. F. C. Armistead and A. L. Tirico. Iss. 2/28/61. App. 5/8/53. Assign. Texaco Development Corp.

Analysis Techniques Based on Nuclear Magnetic Resonance. An nmr core testing device in a drill collar having a test coil around an inner tube through which a small core passes with space outside the coil for passage of drilling fluid, the electronic components being housed in an annular enlargement of the drill collar.

U. S. No. 2,973,472. E. F. Egan, R. L. Kister, and M. B. Scott. Iss. 2/28/61. App. 10/6/54. Assign. Texaco Inc.

Graphical Methods for the Interpretation of Dipmeter Logs. A graphical method for determining the true dip of a formation from information including the log of a dipmeter having three arms at 120° in a plane normal to the borehole, the azimuthal orientation of one of the arms of the dipmeter, and the diameter and inclination of the borehole.

U. S. No. 2,973,477. J. Lerner. Iss. 2/28/61. App. 10/27/58. Assign. Sun Oil Co.

Interface Detection in Deep Holes. A system for locating the interface in a storage cavern by lowering a resistance measuring sonde through a small diameter pipe that terminates at a known depth so that the distance from the end of the pipe to the interface can be measured by the cable paid out between indications.

U. S. No. 2,973,505. O. M. Johannesen. Iss. 2/28/61. App. 10/18/54. Assign. Dresser Industries, Inc.

Method and Apparatus for Earth Borehole Investigating and Signaling. A system for resistivity logging while drilling and having a bridge circuit housed in a drill collar with a timed sequence of substituting balancing resistors in one arm of the bridge and those resistors producing underbalance effecting a pulse on an

electromagnetic valve in the drill stem whose pressure pulses are detected and interpreted at the surface.

MISCELLANEOUS

U. S. No. 2,967,938. A. S. McKay, A. H. Lord, Jr., and R. W. Johnston, Jr. Iss. 1/10/61. App. 2/9/56. Assign. Texaco Inc.

Thickness Measurement. A thickness gauge having a source of fast neutrons and a gamma-ray detector that measures either gamma rays due to inelastic scattering of incident neutrons or gamma rays induced by thermal neutrons produced by moderating the incident neutrons with a hydrogenous substance on the opposite side of the material being tested.

U. S. No. 2,968,762. N. A. Schuster. Iss. 1/17/61. App. 10/21/54. Assign. Schlumberger Well Surveying Corp.

Magnetic Resonance Methods and Apparatus. A magnetic resonance apparatus in which an alternating magnetic field is applied to the sample at right angles to a fixed field and at the resonance precession frequency, and the phase of the alternating field is periodically reversed before the particles attain thermal equilibrium.

U. S. No. 2,968,987. J. J. Knopow. Iss. 1/24/61. App. 6/1/49.

Method and Apparatus for Measuring Depths of Water and Detecting Submerged Bodies by Employing Pulsed Light. A system for detecting objects submerged in water by emitting a short pulse of light, generating an electric signal that subsequently varies as the illumination returning from the water with no object present, generating an electric signal that varies as the observed returning illumination, and comparing the two electric signals.

U. S. No. 2,969,503. W. M. Bustin. Iss. 1/24/61. App. 12/6/57. Assign. Esso Research and Engineering Co.

Measurement of Potential Gradients. A device for exploring the electrostatic field inside an oil storage tank with a movable probe that emits a radio signal whose frequency is a function of the magnitude of the vector component of potential gradient sensed by the probe, the signal being picked up by an antenna inside the tank and indicated.

U. S. No. 2,970,879. J. S. Shulz. Iss. 2/7/61. App. 4/11/57. Assign. Eastman Oil Well Survey Co.

Drilling Recording Chart Holder. A cylindrical chart holder for a drilling rate recorder having at each edge where the ends of the chart overlap a small cylindrical clamping bar drawn into contact with the chart and cylinder by a spring inside the cylinder.

U. S. No. 2,971,189. C. E. Hastings. Iss. 2/7/61. App. 3/22/57. Assign. Hastings-Raydist, Inc.

Radio System. A heterodyne phase-comparison type of position-determining system employing frequency multiplication and division on the radio frequencies instead of on the heterodyne frequency in order to avoid interference of nearby transmitters with the phase-angle measurement.

U. S. No. 2,971,190. H. G. Busignies. Iss. 2/7/61. App. 2/24/45. Assign. International Telephone and Telegraph Corp.

Position Finding System. A system for determining the position of a reradiating object with respect to a single transmitting station and a direction finding station by observing the direction of the reradiated wave and the difference in time between the wave from the transmitter and that reradiated by the object.

U. S. No. 2,973,504. R. J. Bobber and C. L. Darner. Iss. 2/28/61. App. 3/26/51.

Sonic Echo System. A source for a pulse-echo locating system of controlled directivity having a piezoelectric transducer and a magnetostrictive transducer connected in series with the phase of one controlled by a parallel circuit.

SELECTED LIST OF U. S. PATENTS ISSUED DURING JANUARY AND FEBRUARY OF 1961

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,966,725	484	2,966,803	16	2,967,083	324
2,966,744	444	2,966,824	444	2,967,119	12
2,966,795	288	2,966,853[a]	232	2,967,214	484
2,966,797	428	2,966,855[a]	136, 360	2,967,239	236
2,966,798	148	2,966,879	200	2,067,241–243	308
2,966,799	288	2,966,953[a]	360	2,967,244[a]	304
2,966,802	4	2,967,016–020	68	2,967,245[a]	304

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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2,967,272[a]	116
2,967,291[a]	352
2,967,292[a]	360, 364
2,967,426	428
2,967,429	460
2,967,447	12
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2,967,947	140
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2,968,034	444
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2,968,724[a]	304, 516
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2,968,727	140, 308
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2,968,734	308
2,968,753	200
2,968,761[a]	220
2,968,762[a]	228
2,968,768	12
2,968,793	324
2,968,798–799	224
2,968,942	428
2,968,943	484
2,968,945	148
2,968,947	288
2,968,949–950	4
2,968,952[a]	180, 484
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2,969,182–184	68
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2,969,910	16
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2,970,256	440
2,970,258	12, 68
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2,970,472–473	148
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2,970,477	412
2,970,479[a]	4
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2,970,666[a]	8
2,970,840	68
2,970,841	224
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2,971,152	12
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2,971,260	16
2,971,364	484
2,971,372	12, 140
2,971,378	200
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2,972,195	16
2,972,250	440
2,972,251[a]	172, 252
2,972,252	460
2,972,255	412
2,972,380	12
2,972,523	168
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2,972,682[a]	304
2,972,731	108
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2,972,740	68
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2,973,140–142	68
2,973,146–147	68
2,973,156	224
2,973,237–238	324
2,973,408	324
2,973,410	224
2,973,413	216
2,973,434	196
2,973,444[a]	304
2,973,471[a]	208, 220
2,973,472[a]	116
2,973,477[a]	116
2,973,478	68
2,973,495	460
2,973,496	288
2,973,504[a]	108, 484
2,973,505[a]	208, 516

CONTRIBUTORS

MICHAEL A. CHINNERY

MICHAEL A. CHINNERY was born in London, England. He received his B.A. degree in Physics at Corpus Christi College, Cambridge in 1957. After working with Seismograph Service (England) Ltd., for a year, he emigrated to Canada, and took his M.A. degree in Geophysics at the University of Toronto in 1959. At present he is working for his Ph.D. degree, which he hopes to obtain shortly. He has worked for Hunting Survey Corporation on several occasions, both as a party chief in the field, and in the capacity of a consultant.

ANDRE CLEMENT

ANDRE CLEMENT received a M.S. degree from the Sorbonne (University of Paris), in 1948, and took his Engineer diploma at Ecole Nationale Superieure Des Petroles at Rueil-Malmaison.

He has been working with Compagnie Generale de Geophysique since 1950, successively as Chief Computer, Party Chief, and Superviser. He is now Chief Engineer in charge of new developments and technical supervision of all Saharan geophysical activities.

He is a member of SEG, EAEG, and the Association Des Techniciens Du Petrole.

G. C. COLLEY

G. C. COLLEY received a B.Sc. (Hons.) degree in Geology at the University of Wales (Cardiff) in 1939. He joined Standard Oil (N. J.) on a gravity survey of England in the same year. After a period in the Radar Branch of the R.A.F. the English survey was continued both in gravity and field geology. Mr. Colley was transferred to the Iraq Petroleum Company at Tripoli, Lebanon, in 1947 as supervisor of gravity and magnetic surveys of the Middle East. He was transferred to the I.P.C. headquarters in London in 1955. Mr. Colley is a member of SEG and EAEG.

ARTEL A. DOULOFF received his B.A.Sc. in Engineering Physics, geophysics option from the University of Toronto in 1958. From May, 1958 to September 1959,

ARTEL A. DOULOFF

he was employed with Hunting Surveys Limited in Toronto, where he undertook various geophysical projects, including aeromagnetic surveying in Argentina. In September 1959, he returned to the University of Toronto where he received an M.A. in geophysics. Upon graduation he joined KCS Limited in May 1960, where he is presently involved in traffic engineering problems.

He is a member of the Association of Professional Engineers of the Province of Ontario and the Society of Exploration Geophysicists.

WILLIAM C. KNUDSEN

WILLIAM C. KNUDSEN was born in Provo, Utah, December 12, 1925. He graduated from the Brigham Young University in 1950 with a major in physics and mathematics. Mr. Knudsen received the Ph.D. degree in physics from the University of Wisconsin in 1954.

From 1954 to the present Mr. Knudsen has been employed by California Research Corporation. His research activities have been in the fields of elastic wave propagation, fluid dynamics, and flow of fluids in porous media. He holds the position of Senior Research Physicist.

Mr. Knudsen is a member of the American Physical Society, Society of Exploration Geophysicists, American Geophysical Union, and Sigma Xi.

CHARLES H. LAYAT was born in Lyon, France in 1928. He was graduated in 1951 from the Ecole Polytechnique (Paris), and received his Engineer's degree in

CHARLES H. LAYAT

1952 from the Ecole Nationale Superieure du Petrole (Rueil).

He joined Compagnie Generale De Geophysique in 1952. He spent a few years in the field as Chief Computor, Party Chief, and Supervisor, after which he was called to Paris to collaborate in C. G. G's Technical Seismic Department, where he was mainly in charge of seismic refraction problems. Since 1959, he has been the technical Inspector of C. G. G's General Management.

NORMAN R. PATERSON was born in London, England, on February 5, 1926. He received his early education in London, England and later at Port Hope,

NORMAN R. PATERSON

Ontario. He obtained his B.A.Sc. degree in Engineering Physics at the University of Toronto in 1950. In 1951 he took his M.A.Sc. at the University of British Columbia, and in 1955 obtained his Ph.D. at the University of Toronto. He also received a Special Diploma from Oxford University in 1943.

During the war he saw service in East Africa and Palestine with the Royal Signals.

During the summers of his University years, Dr. Paterson gained practical experience with the Defence Research Board in Ottawa, the Radar Exploration Company in Western Canada and the United States, and the International Nickel Company in Northern Manitoba. From 1951–1953 he acted as Geophysicist with Imperial Oil Limited in Edmonton, and later from 1955–1956 became Chief of Geophysical Operations for Dominion Gulf Company, working in various parts of Canada. He joined Hunting Survey Corporation Limited as Chief Geophysicist in 1956.

Dr. Paterson has served as President of the Canadian Exploration Geophysical Society; Chairman of the Geophysics Committee, Geology Division, C.I.M.M.; Mining Representative, N.R.C. Associate Committee of Geology and Geophysics; and Associate Editor, Society of Exploration Geophysicists.

Dr. Paterson is a member of the Ontario Association of Professional Engineers, Canadian Institute of Mining and Metallurgy, Society of Exploration Geophysicists, and European Association of Exploration Geophysicists.

DR. LAJOS STEGENA

DR. LAJOS STEGENA, Candidate of Sciences, attended the Technical University of Budapest. At present he is head of a department of the Hungarian State Geophysical Institute "Roland Eötvös," and lecturer at the University of Sciences of Budapest. His main fields of research are seismics, geochemistry, and geothermics. He is on the board of the Geophysical Council of the Hungarian Academy of Sciences and of the Association of the Hungarian Geophysicists.

A biography of S. H. Yungul appears in GEOPHYSICS, v. 26, p. 123.

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with By-laws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

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Lloyd Robert Lipsett (D. H. Parry, C. J. Chapman, J. E. Robinson)

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Ronald E. O'Neal (Leo A. Markley, Robert C. Stone, J. B. Meitzen)

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Charles Roland Scoggins (Wm. J. Fennessey, John W. Bollinger, Robert E. Watson)

Jesse O. Sims

Harold D. Wellman, (R. R. Kitch, J. W. Hoover, N J. Smith, H. E. Stommel)

ANNOUNCEMENTS

DR. WALTER ORR ROBERTS

SEG NAMES KEYNOTE SPEAKER

Keynoter for the 31st Annual International Meeting of the Society of Exploration Geophysicists, November 5–9, 1961, in Denver will be Dr. Walter Orr Roberts, director of the National Center of Atmospheric Research, Boulder, Colorado.

The theme of the meeting is "Exploration in a Changing World," and it is expected that Dr. Roberts will emphasize space exploration's contribution to a changing world.

Dr. Roberts was born in West Bridgewater, Massachusetts on August 20, 1915. He was granted an A.B. degree from Amherst College in 1938, an M.A. and Ph.D. from Harvard in 1940 and 1943 respectively, a D.Sc. (honorary) from Ripon College in 1958, and a D.Sc. (honorary) from Amherst College in 1959.

Dr. Roberts is a member of the Geophysics Research Board, National Academy of Sciences; Chairman, National Science Foundation Panel on Atmospheric Sciences; Chairman, Colorado Weather Control Commission; Associate Editor, "Journal of Geophysical Research"; member, Editorial Advisory Board, "Journal of Planetary and Space Physics"; member and delegate of National Academy of Science, Working Committee on Solar Activity; and a Trustee of MITRE Corporation.

Dr. Roberts is active in the American Geophysical Union, American Meteorological Society, American Astronomical Society, American Rocket Society, American Association for the Advancement of Science, Royal Astronomical Society, American Adacemy of Arts and Sciences, International Astronomical Union, Sigma Xi, Phi Beta Kappa, Newcomen Society in North America, and the Council on World Affairs.

JERSEY PRODUCTION RESEARCH COMPANY BUILDS EARTH SCIENCES OBSERVATORY

Jersey Production Research Company, Tulsa based research affiliate of Standard Oil Company (N. J.) and Humble Oil & Refining Company, have started construction of a specially designed Earth Sciences Observatory near Leonard, Oklahoma, about 20 miles southeast of Tulsa.

This unique installation will allow simultaneous measurement of naturally occurring events in the earth's crust. Some of these phenomena are known to be correlatable, while others are thought to be related. Therefore, it is believed that simultaneous recording and subsequent search for relationships between such events will lead to additional fundamental knowledge and understanding of the processes governing earth crust phenomena.

The new Observatory will enable Jersey Production Research scientists to study such things as local and distant earthquakes, earth tides, earth tilt, geomagnetic field variations, and earth current fluctuations. In addition, selected prominent earth scientists from universities and other scientific institutions will be invited to use the facilities of the Observatory in conducting their independent research.

The installation will include a subsurface vault in which delicate instruments will be mounted on a concrete pier set in bedrock located about 17 feet below

the surface of the earth. This underground arrangement will aid in shielding the instruments from unwanted disturbances and will permit close temperature control.

Several factors governed the selection of the site. The principal criteria were freedom from man-made seismic and electrical disturbances, reasonable depth to massive bedrock, ample area for electrical potential spreads, and proximity to the Jersey Production Research Company's Tulsa Research Center with its data handling facilities.

Most of the instruments have been delivered. It is anticipated that the Observatory will be completed and in partial operation by the latter part of this summer. As part of the research work to be conducted at the site, several holes will be drilled to depths of 2,000–3,000 feet for the purpose of emplacing instruments.

ABSTRACTS

Bulletin (Izvestiya) September, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

A Rayleigh-Type Wave at a Non-Free Surface

G. S. Pod"yapol'ski and Yu. I. Vassil'ev

The paper adduces some experimental data and theoretical explanations of a specific low-frequency wave originating at a sharp interface, which is similar to a Rayleigh wave at the free boundary of a half space.

Methods of Ultrasonic Seismic Modeling

M. B. Rapoport

Some problems arising in modeling are examined: forming of the wave impulses, direction of the pickups, suppression of Rayleigh waves. The procedures proposed with respect to methods have been tested on solid two-dimensional models, but they may also be used in studies made on three-dimensional models.

Construction of Gradient Maps of the Rate of Vertical Tectonic Movements of the Crust, Based on an Example from the Northern Tien-Shan

G. I. Reisner

Effects in Earth Currents Caused by High Altitude Atomic Explosions

V. A. Troitskaya

Note: Despite the world-wide publicity attending the initial appearance of this paper, the published results were completely anticipated by the French. As a matter of fact, the anticipating paper, Analyse Expérimentale des Effets Magnétiques et Telluriques de "L'Expérience Argus" Enregistrés par les Stations Francaises, S. Eschenbrenner, et al., *Annales de Géophysique*, Vol. 16, No. 2, pp. 264–271, April–June 1960, appeared in print approximately simultaneously with the submission for publication of the Russian paper.

Laboratory Criterion of the Magnetic Stability of Rocks

G. N. Petrova and V. A. Zhilyaeva

The General Solution of a Dynamical Problem for a Visco-Elastic Half-Space

N. M. Borodachev

The Accuracy of the Method of Average Velocities in the Seismic Study of Refracted Waves

E. K. Lossovski

Validity of Determining the Intensity of Earthquakes by Surface Waves

E. F. Savarensky and G. G. Obukhov

On Magnetic Anomalies ΔT of an Arbitrary Intensity

S. N. Gorodensky

Absorption of Ultrasonics in Granites

O. I. Silayeva and O. G. Shamina

Dispersion of Surface Waves and Crustal Structures

V. M. Arkhangel'skaya

Bulletin (Izvestiya) October, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

The Physics of the Earth's Core. Thermodynamic Properties. I.

V. N. Zharkov

Evaluation of the Intensities of Seismic Waves which are Reflected from a Very Weak Boundary of Separation

K. I. Ogurtsov

The intensities of reflected waves are studied for vertical incidence with a consideration not only of the zero (acoustical) approximation, but also of the first approximation, which is the next term of the asymptotic series representing the solution. It is shown that in the case of a very "weak" boundary of separation, the first approximation may be comparable or even large in comparison with the zero approximation.

Questions Concerning the Theory of the Long-Period Vertical Seismometer

V. T. Archangel'sky

The theory of suspension of the pendulum for a vertical seismometer is considered and basic terms in

the equation of motion of the pendulum are shown which give rise to its instability when its period is increased.

On Diffraction Taking Place in Absorbing Media Along a Half-Plane

V. N. NIKITINA

The article discusses the problem of diffraction of an electromagnetic field along a half-plane in a uniform conductive space. The influence exerted by the absorbing properties of the enclosing medium on the relative intensity of the diffracted electric field is examined. Conclusions are drawn with respect to the domain of applicability of the method of radio-wave sounding.

The Mathematical Processing of Geophysical Data

A. G. TARKHOV AND A. A. SIDOROV

Different methods of mathematical processing should be applied to the results of geophysical observations with the object of decreasing the influence of the various types of interference. In addition to the calculation of the arithmetic and geometric means, the use of the so-called method of inverse probability has been recommended. It is shown, by applications to actual material, that the ratio (anomaly/interference) can be increased. The directions for possible future investigations are indicated.

Dispersion of Long-Period Love Waves in the Continental and Oceanic Crust Along the Path Indonesia-Crimea

I. I. POPOV

The Structure of Microseisms and Methods of Determining the Direction of the Source of Their Origination

F. I. MONAKHOV AND N. A. DOLBILKINA

An Experimental Study of the Peculiarities of Longitudinal Waves Reflected from a Thin Layer

S. P. STARODUBROVSKAYA

Recording Earthquakes Utilizing Simultaneously Two Levels of Sensitivity with the Two Galvanometer Seismograph

A. G. MOSKVINA AND N. V. SHEBALIN

A Direct Method of Interpreting Anomalies Δg

N. L. AFANAS'EV

Application of the Method of a Rotating Magnetic Field in Electrical Logging

YU. B. SCHAUB

On the Question of the Magnetic Anisotropy of Layered Rocks

D. M. PECHERSKI

The Approximate Graphical and Graphical-Mechanical Calculation of the Schwartz and Poisson Integrals

A. B. SHTYKAN

Thermostat with Continuous Regulation

V. A. TULIN

The Electromagnetic Field of a Transmitter for Large Values of the Product of the Complex Wave Number and Transmitter-to-Receiver Distance

YU. N. KOZULIN

The Zone of Disturbance of the Thermal State of Rocks by Drilling a Borehole

G. A. CHEREMENSKI

Session of the Council on Seismology

Bulletin (*Izvestiya*) November, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

Physics of the Solid Earth

Physics of the Earth's Core II: Mechanical Properties and Viscosity

V. N. ZHARKOV

The hypothesis of Gutenberg according to which the wave dispersion in Bullen's *F*-layer is caused by a viscosity gradient in that layer, is further analysed. Two very simple models of the Earth's core are investigated.

Some Results of the Investigation of P_a and S_a Waves from the Seismograms of Stations of the USSR

V. V. KHOROSHEVA

By the seismograms of stations of the USSR, investigations are carried out of P_a and S_a waves, the origin of which is related by some authors to a layer with lower velocity in the upper portion of the Earth's mantle. The travel-time curves of the P_a and S_a waves, the approximate value of the geometric-divergence in-

dex, and the absorption coefficient of the P_a wave are obtained.

Utilization of Converted SP Waves of Local Earthquakes in Studying the Structure of the Deeper Crust

N. K. Bulin and E. I. Tryufil'kina

Time Distribution of Elastic Pulse Energy During Destruction of Rocks

A. G. Konstantinova

Analysis of the time distribution of elastic pulse energy reveals certain aspects of the fracturing process during destruction of rock specimens under mono-axial compression, and in coal seams during periods of preceding sudden discharges of coal and gas.

Determination of the Energy of the Earthquake of 11/15/59

V. L. Belotelov, E. F. Savarensky and D. V. Feofilaktov

The Resolving Power of the Magneto-Telluric Method

N. P. Vladimirov and M. V. Kolmakov

Theoretical studies made for a geo-electrical section of type $\rho_1 < \rho_2 < \rho_3 = \infty$ indicate that the magneto-telluric method, in comparison with the method of resistances to a direct current, has a greater resolving power in the development and following of layers of adequate thickness. However, because of the applicability of the principle of equivalence this method likewise cannot independently solve the problem of separating in a section layers of a low degree of thickness.

A Two-Dimensional Model of a Seismic Waveguide with Soft Boundaries

L. N. Rykunov, V. V. Khorosheva and V. V. Sedov

1. The ability of some materials to alter their elastic properties with a change in the temperature makes possible the building of solid models of stratified media with eroded and abrupt boundaries, as well as media having smoothly-changing velocities.

On the Application of the Expressions of a Distant Zone for Electromagnetic Frequency Soundings

D. N. Shakhsuvarov and E. V. Rybakova

The Directed Reception of Secondary Signals in Electro-Prospecting by the Method of a Rotating Magnetic Field

Yu. B. Schaub

PERSONAL ITEMS

DR. A. W. MUSGRAVE RECEIVES GOLD MEDAL

DR. ALBERT W. MUSGRAVE, computer designer and now a Mobil Oil Company geophysicist, has been named the 1961 recipient of the Colorado School of Mines van Diest Gold Medal.

Dr. John W. Vanderwilt, Mines president, announced the award and stated Dr. Musgrave would receive the medal during the School's 87th annual Commencement, June 2.

Dr. Musgrave, a 1947 Mines graduate and currently a resident of Dallas, Texas, worked as a seismologist for Mobil until returning to Mines for doctoral studies in 1950. While a doctoral candidate he formulated and designed the Raypath Plotter, a pioneering analog computer designed for use with seismic reflection interpretation. He received his Doctor of Science degree in geophysics in 1952.

After eight years with various Mobil geophysics departments, Dr. Musgrave was appointed Superintendent of Special Geophysics Problems in March of 1960. He is responsible for magnetic tape playback and special interpretation problems.

The van Diest Gold Medal was established in 1950 by Dr. Edmond C. van Diest, a Mines graduate of 1886. The coveted award recognizes Mines alumni who perform outstanding achievements within five to 15 years following graduation.

The medal has been awarded only twice previously. In 1955 it went to Walter E. Heinrichs, Jr., president of the Heinrichs Geoexploration Co., Tucson, Ariz. Last year the medal was presented to Stanley J. Marcus, technical manager of Lockheed Aircraft's Missile and Space Division Project.

W. W. GREEN is now a Vice-President of Varel International. His new address is: c/o Varel-Afrique, Boite Postale No. 16, La Reghaia, Algeria.

HANS LUNDBERG and Airborne Explorers Limited have new offices in Suite 512, 67 Yonge Street, Toronto 1, Ontario.

H. B. FERGUSON is now manager of the Geophysics Dept. at the Sperry Rand Research Center in Sudbury, Massachusetts. He is setting up a department to do research in earth physics and atmospheric physics with emphasis on fundamentals.

E. P. NEAL, formerly with Kirby Petroleum Co., is now an Independent Geologist in Tulsa. His address is 1443 South Norfolk, Tulsa 20, Oklahoma.

THOMAS A. MANHART, Chairman of the board for Century Geophysical Corporation, has been awarded the Distinguished Achievement Medal by the Colorado School of Mines. The silver medal is the highest honor which the school may bestow upon an alumnus and is equivalent to an honorary doctorate. Mr. Manhart was Secretary-Treasurer of the SEG in 1947–1948 and recently, during the 14th annual Midwestern Meeting, he received the Society's 25-year Award commemorating 25 years of continuous membership.

Sterling silver degrees were awarded to the following six members of SEG during the 87th annual Commencement ceremonies at the Colorado School of Mines, June 2nd: DAVID COOLBAUGH, D.Sc.-geophysics; FRANK HADSELL, D.Sc.-geophysics; DONALD JOHNSON, D.Sc.-geology; RICHARD BUBLITZ, M.S.-geophysics; LATHROP DENSLOW, M.S.-geophysics; and ROBERT SIMS, M.S.-petroleum refining.

CECIL H. GREEN, GSI's Honorary Board Chairman, received an honorary degree from Sidney University. In a period of more than one hundred years, honorary degrees from Australia's Sydney University have been bestowed on only forty men. In a ceremony held in Sydney University's Senate Room on March 6, Chancellor Sir Charles Bickerton Blackburn conferred the honorary degree of Doctor of Science on Mr. Green in recognition of his many accomplishments and continued activities directed toward assisting education in the sciences.

FLOYD L. CASH, Arlington State College, has been elected Editor of the Society of Professional Well Log Analysts.

H. GUYOD, Consultant, has been elected a Member-at-Large of the Society of Professional Well Log Analysts.

BEN F. RUMMERFIELD, geophysical consultant, 6787 Timberlane, Tulsa, Oklahoma, has been cited by Lt. Gen. George W. Munday, USAF, for having successfully completed the correspondence course of the Industrial College of the Armed Forces (ICAF). The college devotes itself to the business and scientific aspects of national security. The course is a year in length. Members interested in taking this course may obtain information from Edwin G. Beggs, Colonel USA, Director of the Correspondence Course Division, Industrial Colleges of the Armed Forces, Ft. Leslie McNair, Washington, D. C.

W. H. GAYMAN is now a Staff Engineer with the Jet Propulsion Laboratory of the California Institute of Technology.

W. W. DUNGAN has been promoted to Seismic Party Chief of Mobil Seismic Party #3 in Garden City, Kansas. Prior to this assignment, Mr. Dungan was located in Midland, Texas, with Mobil Oil Company.

J. B. PITTS, a Vice-President and a Director of Tex-Tube, Inc., Houston, Texas, for the past 14 years, has resigned effective June 1, 1961. He plans to devote his full time to outside interests and travel.

RAVINDRA N. GUPTA has been awarded a Commonwealth Scholarship by the Government of Canada for graduate work in Geophysics leading toward the degree of Doctor of Philosophy. He will pursue his studies in the Dept. of Physics of the University of Toronto. He was granted a B.Sc. (hons.) in Geology and Geophysics, and a Master of Technology in Exploration Geophysics, both from the Indian Institue of Technology, Kharagpur. He is a member of SEG and EAEG.

ROBERT G. VAN NOSTRAND has been named by Rogers Geophysical Companies of Houston to serve as an executive of Exploration Geophysique Rogers. The latter firm is Rogers' operating company in Europe and North Africa.

This new post with Rogers will return Dr. Van Nostrand to France where he has lived for the last three and one-half years serving as Chief Geophysicist for the Societe de Prospection et Exploitations Petroliers en Alsace. His new headquarters will be in Paris.

A native of Oneida, New York, Dr. Van Nostrand received a Bachelor of Science degree in physics from the Missouri School of Mines in 1942. Following a tour of duty with the United States Army in the European Theatre of Operations during World War II, he returned to the Missouri school to teach physics and geophysics for two years.

Dr. Van Nostrand earned his doctorate at the University of North Carolina, specializing in physics and geology. While working toward this degree he was associated with the U. S. Geological Survey.

He has previously been associated with the Magnolia Petroleum Company Field Research Lab., doing research in applied geophysics; and with the Mobil Overseas Oil Co., assigned in Portugal and France.

A former Assistant Editor of GEOPHYSICS, official publication of the Society of Exploration Geophysicists, Dr. Van Nostrand has authored some 12 papers on mathematics and the applied geosciences. He is a member of the SEG, the European Association of Exploration Geophysicists, and the Association Francaise des Techniciens de Petrole.

RUFINO GEA has joined the staff of Aero Service (Bahamas) as Manager of its Ground Geophysics Department. Previously he was with Geoprosco, Madrid.

A doctor of mining engineering, Gea was graduated from Escuela Técnica Superior de Ingenieros de Minas of Madrid. He was associated with the Geophysical Department of the Geological Institute of Spain for a time, then gained field and administrative experience in technical and staff assignments with a geophysical company.

He also served as Vice Secretary and Professor of the Department of Applied Geophysics of the National Institute of Geophysics of Spain. Later he held posts as chief engineer of the Geophysical Dept. of Compañía Española de Cimentaciones y Sondeos S.A., and as managing director of Compañía de Prospección Geofisíca S.A. (Spain).

Mr. Gea has a broad background in geology and geophysics as applied to water, oil, and mining exploration problems. He has been engaged in exploration projects in Spain, Portugal, Great Britain, France, Morocco and the Spanish Sahara since 1949. He is a member of Instituto de Ingenieros Civiles (Spain), Colegio Oficial de Ingenieros de Minas (Spain), Society of Exploration Geophysicists, American Geophysical Union, and European Association of Exploration Geophysicists.

DR. J. E. HAWKINS, formerly Vice-President in charge of research and development, has been named Executive Vice-President in charge of Seiscor, a division of SSC. In this post he will be in charge of all manufacturing and research facilities, and all product and military sales for the company.

LOUIS W. ERATH, formerly Senior Vice-President of the SIE Division of Dresser Electronics, has announced the formation of a consulting firm bearing the name "Erath, Inc.," with offices at 1223 Waugh Drive, Houston, Texas. Mr. Erath states that he and his associates will offer their services to industry in the Southwest as consultants and advisors in the use and design of electronic instruments. The company is particularly interested in instrumentation for the oil and petro-chemical industry which abounds in the Gulf Coast Area.

RICHARD KEELING, formerly with SIE, has joined Hall-Sears, Inc. as Chief Engineer. Mr. Keeling is a veteran of thirty-two years experience with geophysical instruments. Prior to working at SIE, he was associated with Seismic Explorations, Inc. and Sun Oil Company.

BILL NEWTON recently joined Hall-Sears, Inc. to become Manager of their European operations. Mr. Newton was formerly associated with the Robert H. Ray Company, and prior to that, General Geophysical Company.

EDWIN B. NEITZEL has been appointed Chief Research Engineer for Geophysical Service Incorporated. Prior to this appointment he was Group Head for Advanced Planning for the Switching Division at Collins Radio, and before this he was Technical Supervisor of the Geophysical Laboratory of the Atlantic Refining Company.

DREW HUDSON, formerly a Manager with the Industrial Products Department of the Canadian General Electric Company Limited, has joined the legal firm of McKeown, Yoerger, Chown & Hudson, as a partner.

DR. P. EDWARD BYERLY, recently with the U. S. Geological Survey, Washington, D. C., has joined the staff of the La Habra Laboratory as research geophysicist.

INDEX GEOPHYSICAL SURVEYS CORP., Houston and Dallas, Texas, announces the addition of EARL C. THOMAS to its staff as Geophysical Supervisor and Staff Co-ordinator of all operations. Mr. Thomas, a graduate of Trinity University in mathematics and physics, has had extensive experience in the Gulf Coast, West Texas, and Rocky Mountain areas.

VIRGIL E. BARNES, Director, Tektite Research, The University of Texas, and Mrs. Barnes have returned from a seven-month survey of tektite localities, meteorite craters, and tektite collections in Europe, Asia, Australia, and Africa. Dr. Barnes is on leave of absence from his position as Research Scientist with the Bureau of Economic Geology and Professor of Geology until September 1. Dr. Barnes' research on tektites is supported by a grant from the National Science Foundation.

W. D. DAUPHIN has been appointed Personnel Director of Independent Exploration Company, Houston, Texas.

Dauphin, a 25-year veteran with Independent Exploration, started working for the firm as a helper on a seismic crew in 1936. He has worked at almost every

job in a field crew up to Party Chief. Dauphin's most recent assignment was as Assistant Manager of Independent's Weight Dropping Division at San Angelo, Texas.

HERBERT C. SMITH has recently opened offices as consulting Geophysicist and Geologist at 320 Pinehaven Drive, Houston, Texas. Herb was formerly Seismic Supervisor with Seismic Explorations, Inc., Houston, Texas, and more recently was associated with the Reynolds-Southwestern Corp., Houston, Texas, as Vice-President & Geophysicist.

CHARLES E. DAVIS, 28, Geophysicist for Pan American Petroleum Co., Oklahoma City, was killed in an auto accident April 11, 1961, in Oklahoma City. Though he had resigned from SEG in 1958, Mr. Davis was quite active in the Geophysical Society of Oklahoma City, serving as Finance Chairman of the 14th Annual Midwestern Meeting. The tragedy occurred within an hour after the meeting closed. In lieu of other remembrances, the family has suggested that contributions be made to the Charles E. Davis Memorial Fund at Graystone Presbyterian Church, 830 Graystone Street, Oklahoma City, Oklahoma.

EWIN D. GABY, President of Delta Exploration, Inc., Jackson, Miss., was killed in an automobile accident in Jackson on Memorial Day.

Mr. Gaby had been an Active member of SEG since 1936.

FRED KAFKA, Manager of Exploration in the Spanish Sahara, assigned to Spanish Gulf Oil Company, lost his life in a fishing accident, Sunday, February 26, 1961. He was fishing from the rocks at Las Palmas, Canary Islands, where he was stationed. His two young sons were near him and his wife and a friend were also nearby. Apparently a large wave struck him, knocked him against the rocks and washed him into deep water. The water was very rough, and his wife and her friend were unable to make any rescue efforts. It was a couple of hours before his body was recovered. He was buried in the British Cemetery at Las Palmas on February 28, 1961.

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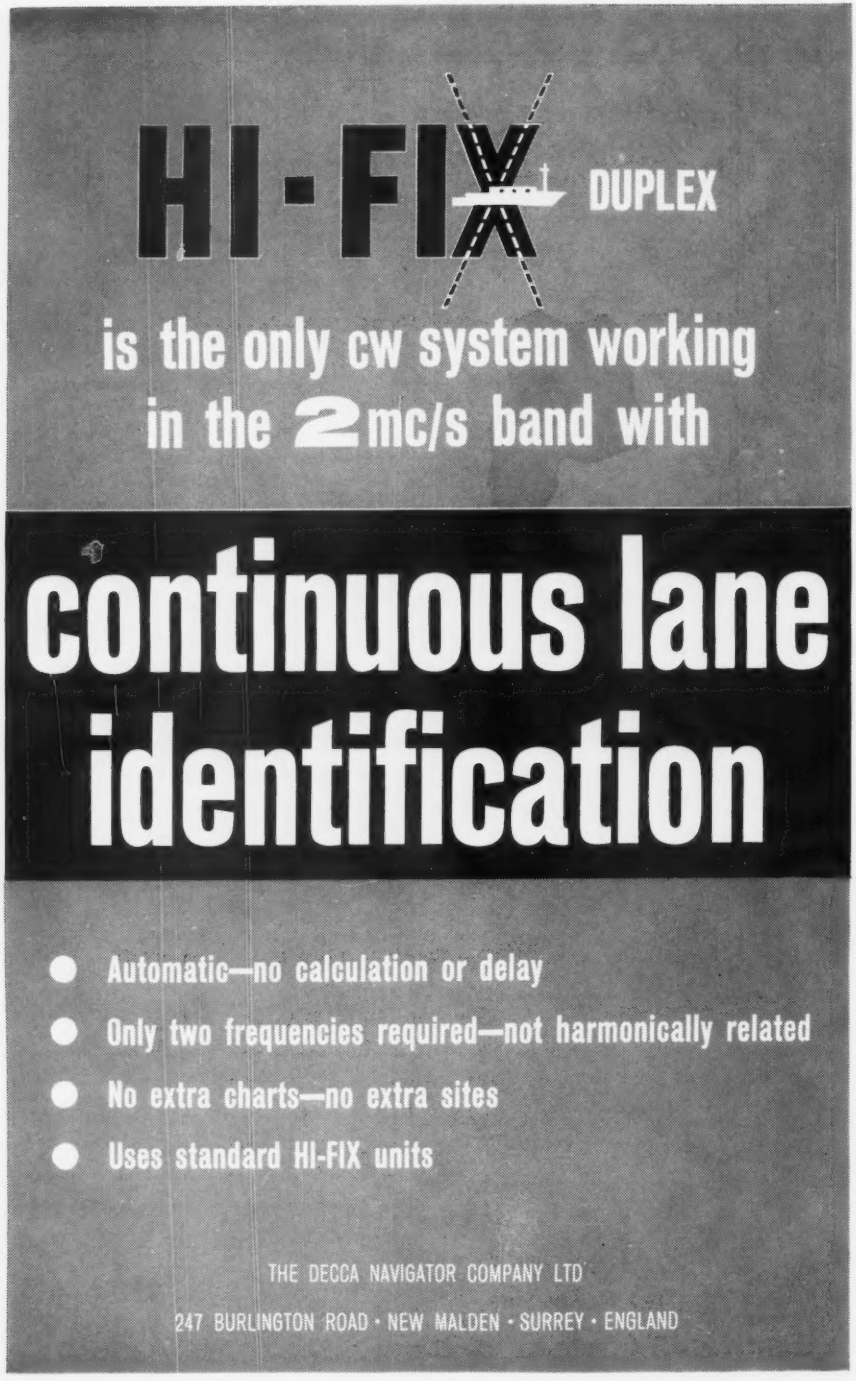
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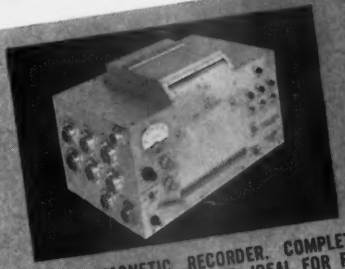

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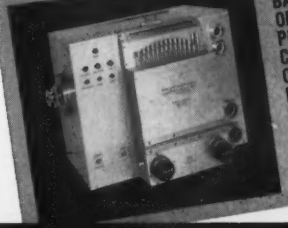

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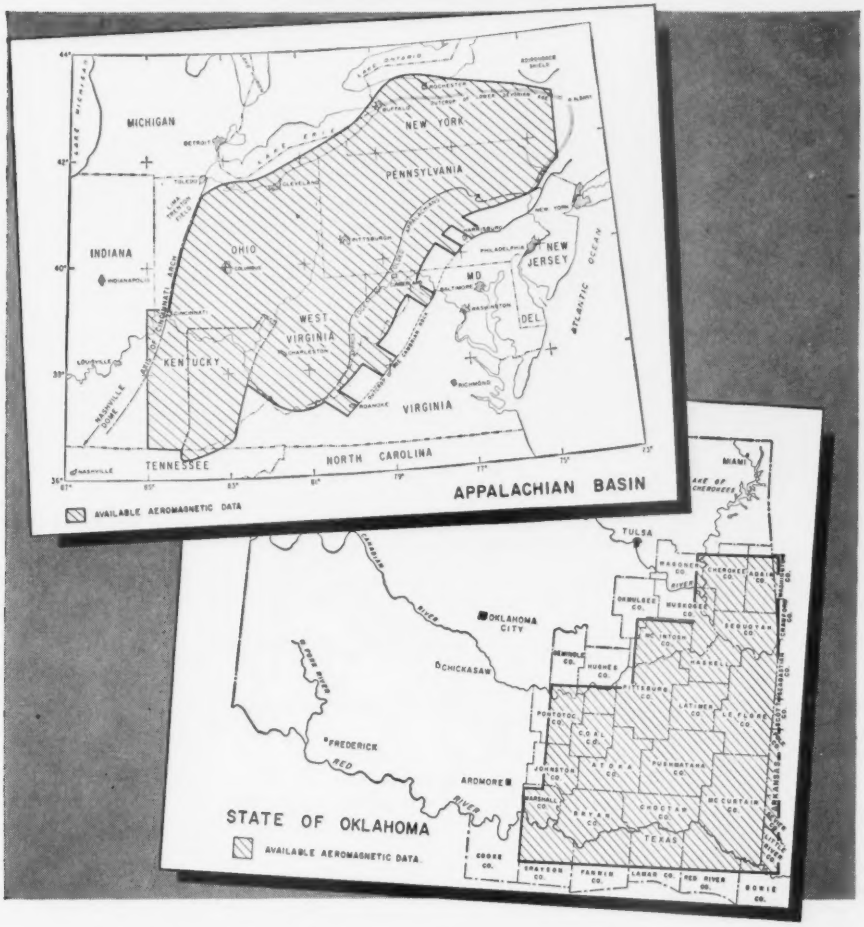

Appalachian Basin: An area of approximately 129,000 square miles. Profile direction is NW-SE in most of Appalachian Basin area; N-S in most of New York State. Map scale is 1:100,000. Contour interval is 10 gamma; in areas where magnetic relief is very low, 5 gamma. Regional gradient is determined on basis of recognized up-to-date charts and removed in compilation process.

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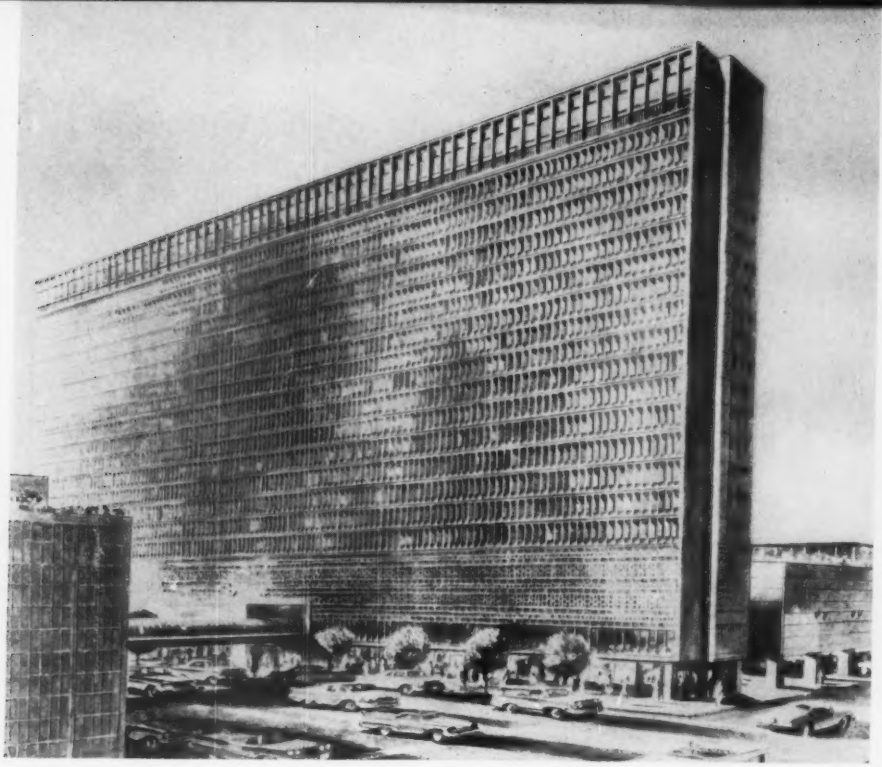

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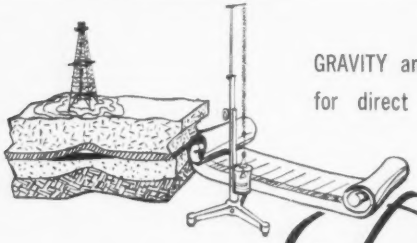

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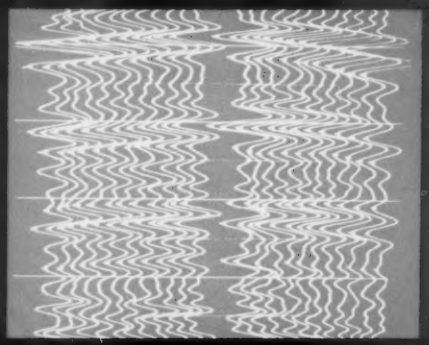
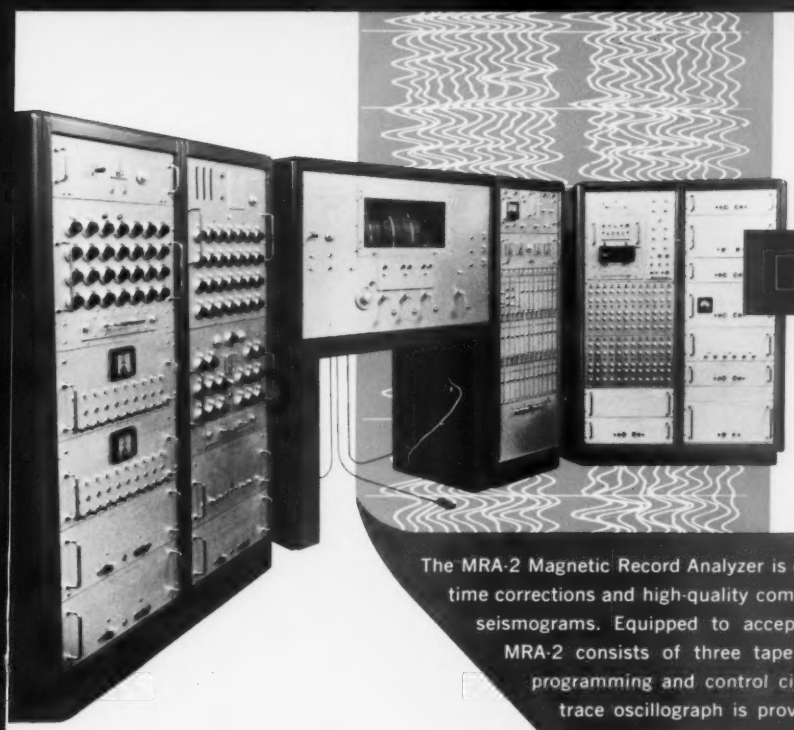


ELECTRO-TECH PLAYBACK SYSTEMS

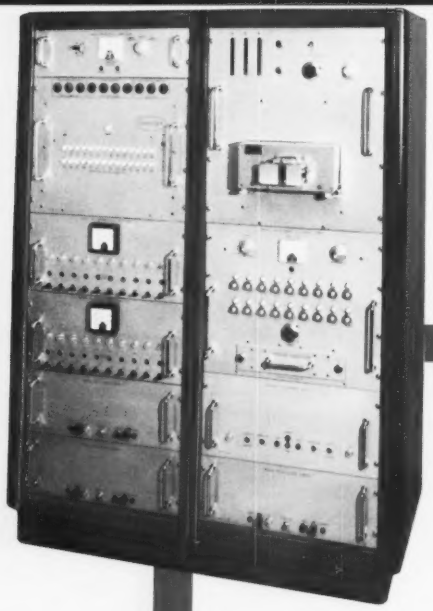


MRA-2

MAGNETIC RECORD ANALYZER

The MRA-2 Magnetic Record Analyzer is designed to provide very precise time corrections and high-quality composites of magnetically-recorded seismograms. Equipped to accept FM-recorded field tapes, the MRA-2 consists of three tape drums, a memory drum and programming and control circuits. A precision-speed, multi-trace oscillograph is provided for the final display. Time corrections, both static and dynamic, are introduced sequentially, trace-by-trace, as the field recording is played back. The moving head on the time correction drum of the MRA-2 is governed by an extremely high-quality servo which continuously solves, with precision, the normal moveout equation from

ELECTRO-TECH



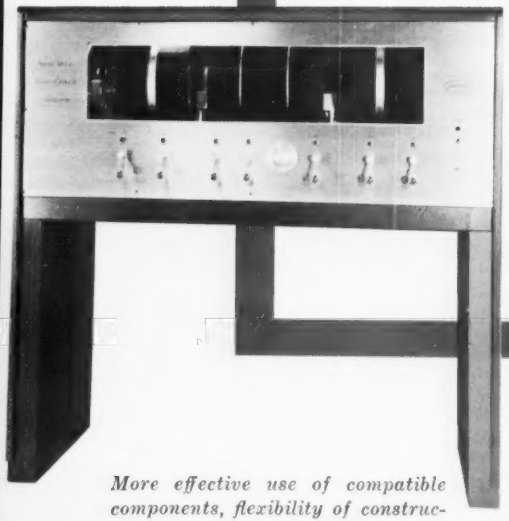
A punched tape reader allowing automatic introduction of static corrections and spread parameters is available as an MRA-2 accessory.

spread length and velocity parameters fed to it by precision multi-turn potentiometers. The potentiometers for each trace, and those governing the velocity function, may be preset before the playback operation begins. The speed of the servo controlled head will allow for normal moveout corrections of up to 1 second in magnitude. Although time corrections are introduced sequentially, trace-by-trace, a full set of modulators, de-modulators and playback amplifiers is provided, allowing one revolution compositing of two or three corrected tapes and simultaneous multi-trace presentation on the oscillograph. The highly-automatic method of introducing time corrections, together with the swiftness of operation afforded by simultaneous multi-trace compositing and presentation, offers unprecedented savings in programming time and cost for processing field tapes.

MRA-3

OFFICE PLAYBACK COMPOSITOR

Designed for high-speed compositing, the MRA-3 is a seven-drum adaptation of the MRA-2, with the same high-performance characteristics. With each drum is a 28-channel bank of record-reproduce heads. The center drumhead bank is movable ± 250 milliseconds around the drum by means of a front panel control. All drums, except the center drum, are rotatable 360° with respect to the shaft, may be locked in any position, and are equipped with verniers calibrated to 1 millisecond. Zero time, as well as seven other timing or sequence functions, is developed with a photocell disc, photocells, amplifiers and relays. Offering a high degree of application flexibility, the MRA-3 may be equipped to composite seven 28-channel tapes in a single revolution, or in a sequential operation. Completely transistorized electronics are available for custom systems.

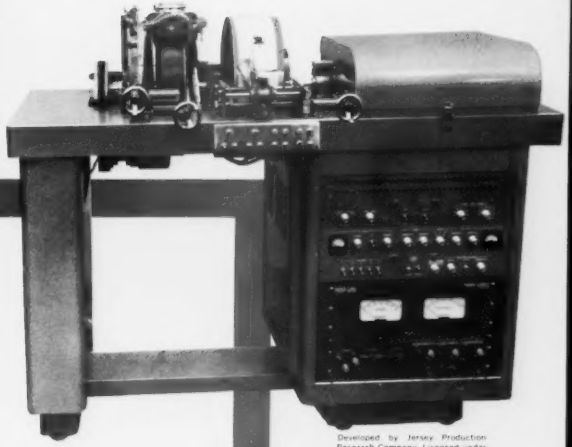


More effective use of compatible components, flexibility of construction and reduced programming time, result in the greatest possible economy in record presentation.

MPS-2

PLAYBACK SYSTEM

The MPS-2 is a versatile and economical magnetic tape playback system. It is a simplified version of the MT-4, sacrificing only the capability of "stacking." Four drums, consisting of a tape drum, memory drum, monitor drum and section drum, accomplish the functions of the MPS-2. Static corrections are provided manually in the standard unit, or automatically when an auxiliary programmer is added. With the MPS-2, large-scale performance is economically available.



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MT-4

OFFICE PLAYBACK SYSTEM

The MT-4 Office Playback System is designed to process field tapes obtained on the FR-1 (Carter) Field Recorder. The MT-4 consists of seven drums mounted on a common rigid aluminum base. These drums include four standard tape drums, one time break alignment drum, one magnetic memory drum and a drum oscillograph. The drum assembly, together with an associated time correction mechanism and control circuits, provides for playing back a field tape, introducing static and dynamic time corrections, and finally displaying it on a record cross section. Operating sequentially, trace-by-trace, the MT-4 introduces time corrections to a field tape and re-records the corrected trace onto a second drum, at the same time recording this trace on the drum oscillograph after playing it back through a seismic amplifier with filters and AVC. As many as four time-corrected records may be composited in any one of several available "stacking" programs. Intertrace mixing, within an individual corrected tape, is also available.

The final presentation may be displayed on photographic paper or film in the form of a wiggly line, variable area or variable density. An electrosensitive paper and pen motor combination may also be employed. Available attachments for the MT-4 include an automatic programmer for introducing time corrections from pre-marked cards and an automatic moveover device for advancing the pen carriage in the oscillograph a preset amount on each print cycle.

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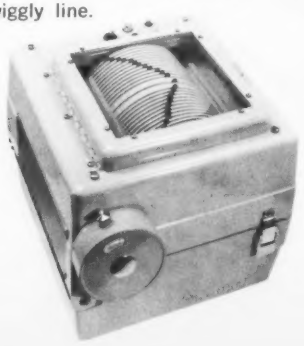
economy in record presentation.

E-336

UNIVERSAL CORRECTOR-ANALYZER

The Corrector-Analyzer is a central office facility designed to process FM magnetic tape recordings made by the weight dropping method. The Corrector-Analyzer was designed as a production tool to facilitate rapid, accurate, and flexible operations in data reduction through automatic programming devices. The machine is a drum-type, sequential tape recording and playback device in which is incorporated two independently operating functions — correcting and compositing.

These functions are (1) the application of static and dynamic corrections to "raw" field tapes to produce tapes corrected for elevation, weathering and step-out . . . and (2) compositing, stacking, and mixing of the recordings from the corrected tapes, as desired, to produce photographic seismograms. Available displays include wiggly line, variable area, variable density and a combination of variable density and wiggly line.



DS-7

FLATBED RECORDER AND PLAYBACK UNIT

The Model DS-7 is a portable, lightweight, direct-recording, magnetic tape recorder and playback unit completely self-contained. Static and dynamic time corrections can be introduced on playback. Reliable under all field conditions, the DS-7 may be easily integrated into existing seismic equipment. The DS-8 model has the tape drive speed adjusted to 3.59 inches per second and head configuration such to provide compatibility with other direct recording systems.

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In addition to the features discussed, Electro-Tech has built into its playback systems many more advanced features.
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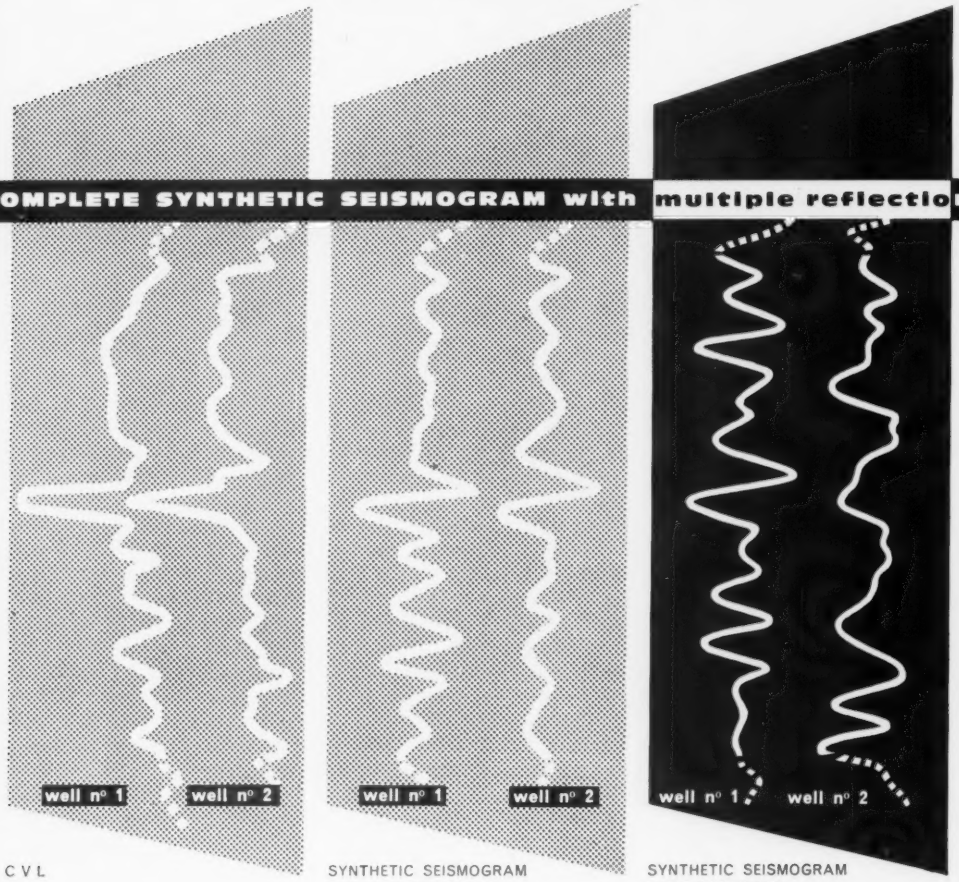

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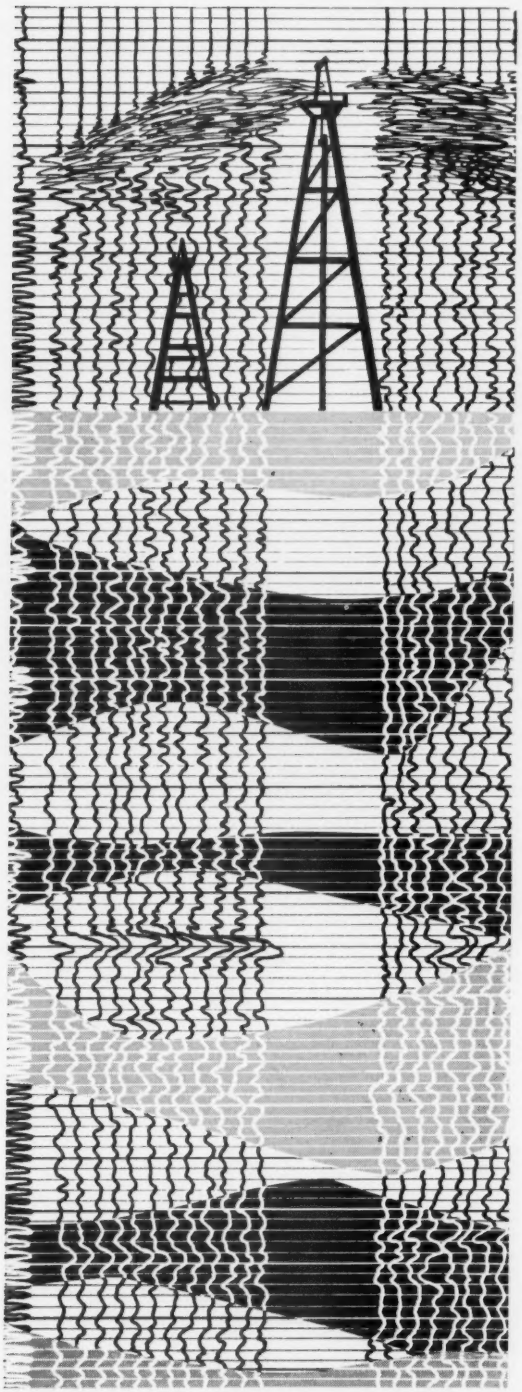

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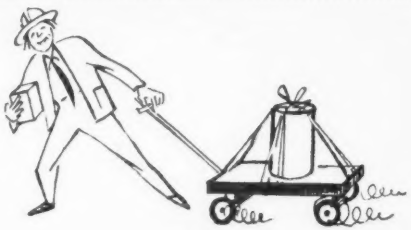
IAGA stresses the importance of having correct measurements (by variographs) at some special "variation repeat stations" for periods of several days. Such repeat stations are particularly needed in regions where the magnetic field is anomalous because of geological conditions, or where it is varying rapidly because of the nearness of the station to the auroral zone. . .

ASKANIA

Recommended by JAGA, JUGG Meeting resolution taken at Helsinki in August 1960



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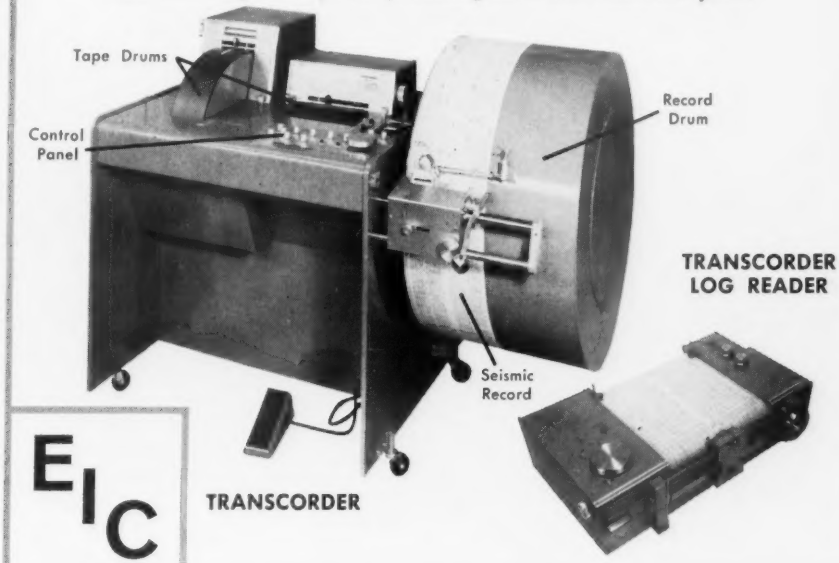
now your tape playback equipment can process data from paper records and well logs

you can often get a more accurate subsurface picture, and thus reduce the likelihood of expensive errors, by transcribing these data onto magnetic tape for processing on a data-reduction system



The Transcorder, EIC's new data-transcribing device, transcribes seismic data onto any standard geophysical tape from paper records, from other sizes of magnetic tape, or, using the Transcorder Log Reader, from well logs. A reproduction of a seismic trace being transcribed can be produced simultaneously for checking purposes.

Magnetic tapes produced by the Transcorder can be processed by playback systems that permit mixing, selective filtering, correcting for moveout, weathering, and elevation, and plotting cross sections by the conventional trace, variable-area, or variable-density methods.

The paper record being transcribed onto tape is mounted on a large revolving drum. The magnetic tape is mounted on another drum that is servo-driven at an infinitely variable rate. The Transcorder will accurately transcribe paper records recorded at speeds ranging from 7.5 to 15 ips. The magnetic recordings produced are accurate within ±1½ ms of the original record at all times.

The Transcorder operator guides the tracking head as the record-carrying drum revolves. (Unskilled office personnel can operate the Transcorder.) The traces are individually transcribed to magnetic tape.

The Transcorder Log Reader, an accessory, permits transcribing well logging data onto magnetic tape in the same manner as conventional seismograms. The resulting tapes can be then converted to cross sections by seismic data reduction systems.

Write or wire EIC for detailed specifications

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this complete 24-channel seismic system produces high-quality tape-recorded data, keeps your operating costs and field-equipment investment low

EIC

Although it weighs only 157 lb, the PSS-50 is a complete seismic system, consisting of two 12-channel seismic amplifiers, a tape-transport unit, a translator unit, and a master control unit.

The system's low cost and weight were gained by designing it to utilize fully the capabilities of magnetic tape and by including only needed filtering and display capabilities. The result is a truly portable system that performs superbly.

The seismic amplifiers have a flat frequency response from 8 to 250 cps. Filtering is provided by a separate plug-in unit. Filtering available includes 12 to 24 db per octave slopes, with 20, 30, and 40 cps cutoff points. Cutoff frequencies can easily be changed by plug-in capacitance boards.

A master control unit provides uphole level control, leakage and continuity testing, trip indicator and manual control, trip sensitivity control, master suppression control, avc on-off control, and a test oscillator. Timing accuracy is ±1 ms.

The tape transport unit has a full 28-channel magnetic recorder, featuring standard EIC door-mounted recording heads. Heads can be interchanged without disassembling the tape transport. Recording heads have excellent low-frequency and transient response. The accurate, reliable drive system uses a hysteresis synchronous motor and a spur-gear transmission.

The translator unit has a playback amplifier with additional avc and filtering control. Traces are displayed on electrosensitive paper by a rectilinear pen writer. Each data channel is played out sequentially and automatically. Timing is provided by preprinted timing lines, with the 100 cps timing trace from the tape played out as a check. Two paper speeds are available, one for a full-length record, the other for expanding the first third of the record (covering the first-break region) over the full paper length. Accuracy from trace to trace is ±1 ms.

Power required for the PSS-50 is 12 v at 8 a during standby and 18 a while recording.

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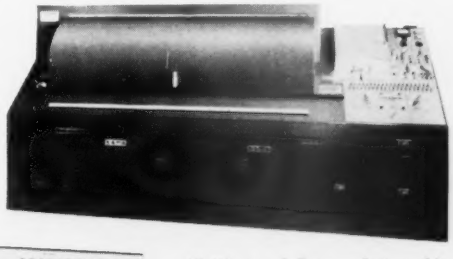
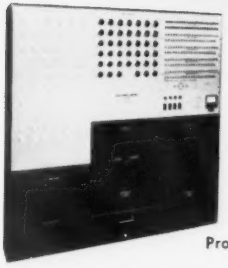
this versatile playback system simplifies your toughest data analysis problems

using EIC's central office seismic data reduction system, you can easily apply precise corrections to field-recorded tapes, use mixing, compositing, or stacking, select the most effective presentation modes

Field Tape Playback Unit



Plotting and Re-record Assembly



Programming Assembly

EIC

C-850

When you own the C-850, you have the most flexible single system available for sequential playback of magnetic tapes. It lets you make maximum static corrections of ±100 ms and dynamic corrections up to 400 ms (at a maximum rate of 500 ms per sec). Timing accuracy is ±1 ms. Any geophone spread length or arrangement can be handled.

During playback, time-corrected seismic data are plotted simultaneously to photographic cross sections. You can choose conventional - trace, variable - area, or variable - density cross sections, or any two of these three. Seismic data can be referenced to any desired datum plane on the cross-section plots. As many as 864 traces can be recorded on a single cross section, which may be as large as 72 x 72 in.

Corrected data are re-recorded during playback for future evaluation. As many as 12 channels of re-recorded tape can be played back for mixing, compositing, or stacking to cross-section plots.

The C-850 can be supplied with any standard-size tape transport. It handles up to 50 seismic and information channels at tape speeds of 7.5, 3.75, or 3.6 ips. It can reproduce direct, FM, or PWM recordings. Re-recording is by FM. Cross-section plotting speed is from 7.5 to 10 ips.

Distortion on FM is less than 1%, on direct magnetic recording, less than 2.5%. Frequency response is from 5 to 500 cps. Signal-to-noise ratio is 52 db (rms-rms) on direct recording, 46 db (rms-rms) on FM.

Such standard EIC design features as door-mounted recording heads and 400-cps hysteresis synchronous motors make the C-850 reliable, easy to maintain, and relatively inexpensive.

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here's a low-cost, rugged field office playback system that really takes abuse

you get simple, precision operation with minimum maintenance costs when you buy EIC's durable, highly accurate field office seismic data reduction system. and it's priced lowest in its field!

PB 50/60

Keyboard Input Unit

EIC

The PB-50/60 sequential playback system was engineered and built to give reliable service under adverse field conditions. Its single-console construction makes it easy to move from one location to another, and its rugged, simple construction makes it easy to maintain. Despite its low cost, the PB-50/60 gives you great flexibility of operation and ±1 ms accuracy.

Normal moveout corrections up to 240 ms are available at a maximum rate of 500 ms per sec. Maximum weathering and elevations corrections of ±100 ms can be applied. All corrections are inserted easily and rapidly by a keyboard input unit.

Timing lines on cross sections are recorded directly from field timing signals, giving you accurate trace plots that are in true relation to each other and to record time. Seismic information can be accurately referenced to any desired datum plane. Either conventional-trace or variable - density cross sections are plotted photographically on 24 x 72-in. tape or film. This system can be supplied with any standard-size tape transport.

Modifications of the basic PB-50/60 can be supplied to meet specific requirements.

Write or wire EIC for detailed specifications

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fidelity, timing accuracy mark this direct recording magnetic tape system

this direct recording magnetic tape system updates seismic systems to provide high-quality tape-recorded data for analysis in seismic data reduction systems

DR-50

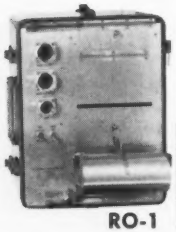
The DR-50 magnetic recording systems produced by EIC record up to 50 seismic and information channels. Record - reproduce heads have excellent low-frequency and transient response. They are mounted on the access door so that they can be inspected, adjusted, or replaced without disturbing the tape transport.

The neatly packaged plug-in amplifiers used as dual-purpose record and reproduce units provide proper playback compensation down to 5 cps.

The DR-50 features timing accuracy of ±1 ms, with trace - to - trace accuracy of ±0.5 ms. Frequency response is from 10 to 500 cps. Signal-to-noise ratio is 52 db (rms). Total harmonic distortion is 2.5%. The DR-50 is driven by EIC's reliable 400-cycle synchronous motor.

The DR-50 is available either with or without a buffer unit. The buffer is used when the seismic amplifier cannot drive the recording heads directly or when a superior signal-to-noise ratio is needed for field playback. EIC engineers are experienced at integrating systems with existing amplifiers and can provide turnkey installation of DR-50 systems.

you get dependable field performance from this rugged recording oscillograph



RO-1

The RO-1 recording oscillograph photographically records up to 28 seismic data traces on 6-in. paper or film. A 400 cps hysteresis synchronous motor provides uniform paper speeds from 3 to 45 ips. Speeds are selected by interchanging easily replaceable drive gears. Precise time correlation is insured by sharply defined timing lines. The RO-1 has 28 pencil-type galvanometers that are available in natural frequencies from 125 to 500 cps. Both galvanometers and front-surfaced mirrors can be adjusted readily in the field. Because the RO-1 produces very little noise in the battery circuit, a single battery can power both the camera and the seismic amplifier. This simplifies battery-charging problems and makes the RO-1 especially suitable for truck mounting.

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cut uphole shooting time and costs with this precision interval timer

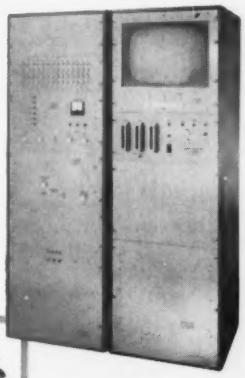
you can obtain weathering and subweathering velocities accurately and efficiently with this interval timer, without using costly seismic recording systems

GT-1

EIC's GT-1 geophysical interval timer is a precision digital readout instrument that simplifies uphole shooting operations. It provides an immediate visual display of the time interval from shot detonation to the initial seismic wave received by an uphole geophone. Accuracy is ±0.5 ms. A maximum time interval of 255.75 ms can be recorded.

The GT-1 is completely transistorized. It is powered by self-contained dry-cell batteries. The unit's total weight, including batteries, is only 17 lb. Its aluminum carrying case is 16 x 9 x 7¾ in.

now you see results of filtering, stacking, mixing without waiting for cross sections



MSS-100

The MSS-100, a remarkable new multitrace electrostatic storage system developed by EIC, lets you store up to 28 seismic data traces for visual readout on a 17-inch, TV-type, video monitor. This advance in the art of handling seismic data can help you cut the cost of analyzing geophysical data.

The MSS-100 stores data from tape-recorded seismic traces in a special storage tube and displays them continuously on the monitoring tube. Traces can be displayed for as long as 20 minutes without appreciable deterioration. They can be erased instantly to permit storing new data.

Vertical timing lines can be displayed on the video monitor at 1/100-second intervals, with 1/10-second lines accentuated. Either the 1/100- or 1/10-second lines can be omitted if desired.

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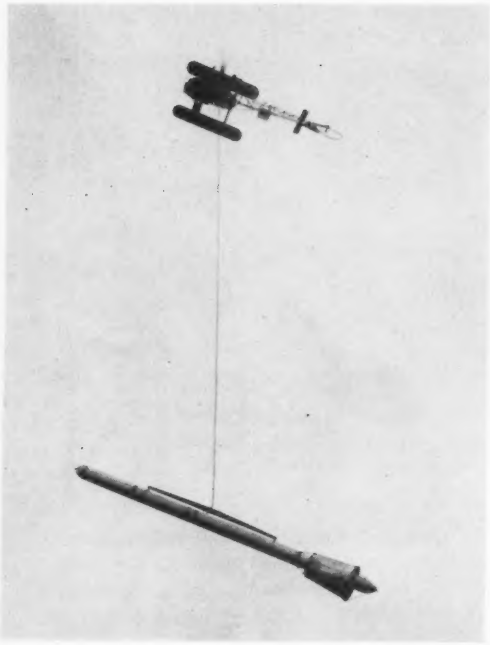

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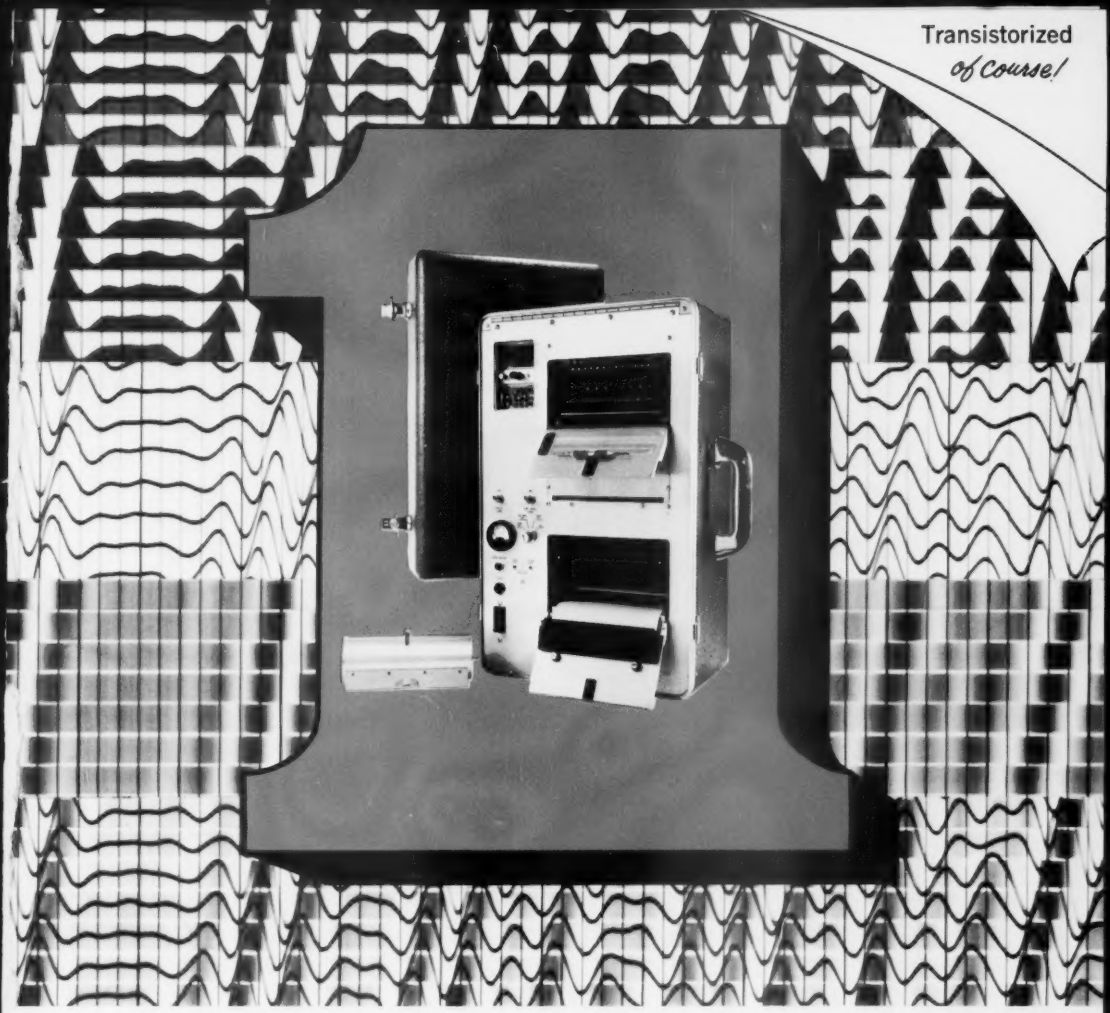

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From SIE comes the first means of obtaining five displays from only one oscillograph . . . and with but one galvo block! ■ Choose variable-density, variable-area, conventional wiggle, **variable-density-and-wiggle** or **variable-area-and-wiggle superimposed.** Simple lens-box change converts from variable-density to variable-area. ■ Timing lines may be generated internally from either flasher tubes or standard timing motor. Consistency of paper drive is assured by a synchronous motor with built-in 400 cps power supply.

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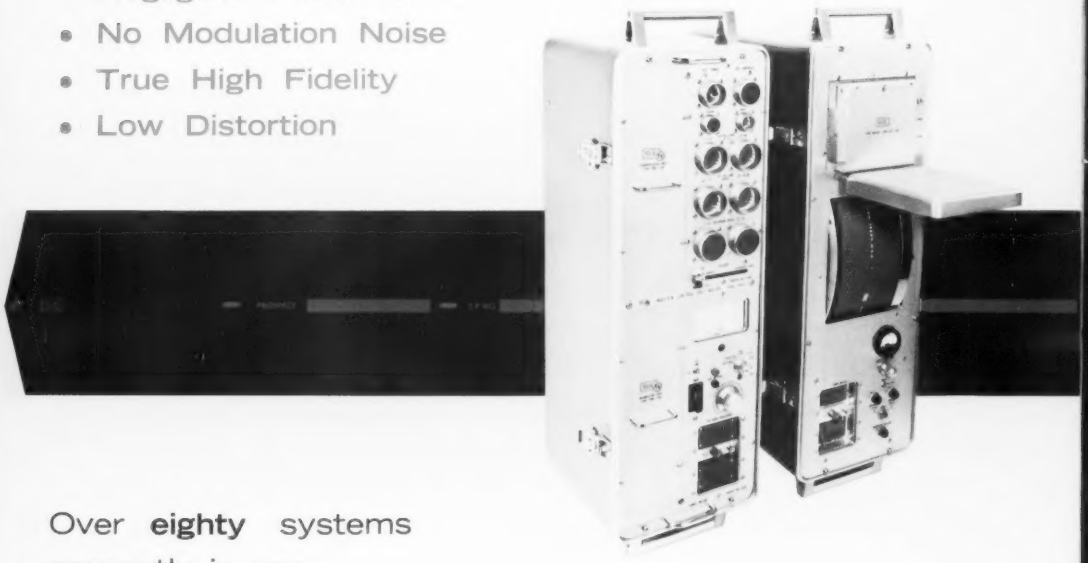

Over **eighty** systems
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supplying full spectrum
High Fidelity FM Magnetic Recordings
for today **AND TOMORROW!**

There is no reason why you should not now record the FULL spectrum of energy in each shot for processing by today's techniques or by whatever better method may be evolved in the future. The SIE PMR-20 "RecorData" FM system gives you such data for refraction, conventional and high-frequency operation . . . and does it all with low-power drain and miniaturized construction. The complete 24-channel transistorized system is housed in two compact, lightweight units. It provides high-fidelity frequency-modulated recordings on standard SIE tapes from the output of standard geophysical amplifiers. System performance is not dependent on tape quality. Look at the brief technical description on the right . . . then write or call for complete information.

CONDENSED SPECIFICATIONS

Channels: 24 geophysical
4 auxiliary (Time break, up-hole, 100 cps and noise cancelling)

Frequency response: 1 cps to 300 cps within 1 db, 3 db down at 500 cps

Signal-to-noise ratio: 60 db (rms), 1 to 500 cps with noise cancelling.
54 db (rms) 20 to 200 cps without noise cancelling.
(Peak-to-peak noise averages 6-10 db higher than rms noise)

Harmonic distortion: Less than 1%

Crossfeed: Below noise level of recording system

Relative timing accuracy: ± 0.25ms.

Power requirement:

	Standby	Operating
Record	2 amp.	7 amp.
Playback	1.5 amp.	6.5 amp.

12 volts D.C.

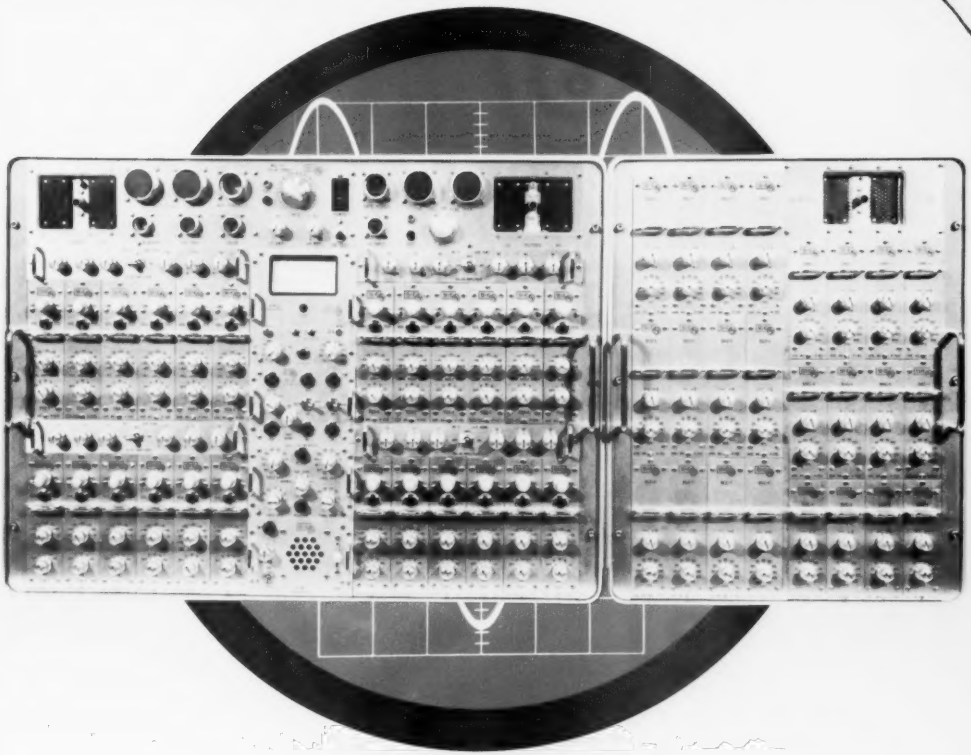
Dimensions: MR-20 Recorder—8¼"W x 24½"H x 15"D
MU-20 Master Unit—8¼"W x 24½"H x 10½"D

Weight: MR-20 Recorder—60 lbs.
MU-20 Master Unit—45 lbs.

SIE'S DISTORTION-FREE

Transistorized *of course!*

PT-100 Transistorized Seismic Amplifier



SIGNAL CONTROL

With unique light-sensitive photocells as losser elements, the PT-100 eliminates the usual amplifier AGC problems. The critical "diode-balancing" common to other types of AGC circuits is never required. There is no direct electrical coupling between AGC and signal paths to cause distortion and oscillation. Signal voltages do not cause distortion when applied across losser elements as with diode bridge circuits. Drift and temperature instabilities are eliminated. There is a useful operating range of from one microvolt to one volt input — 1,000,000 to 1! Total harmonic distortion under all normal field operating conditions does not exceed 0.5% including heavy reflection standout. External 4 kc signals may be used for programmed-gain operation during amplitude studies. AGC performance down to 5 cps allows use of the PT-100 in refraction work **with AGC control.**

FREQUENCY RESPONSE

The broad band response extends from 3 to 500 cps. Ten logarithmically-spaced cut-off frequencies are provided — from 16 to 135 cps for the low-cut and 23 to 235 cps for the high-cut filter positions. One or two sections (18 or 36 db/octave) may be used.

NOISE

Noise is less than 0.3 microvolt for "filter-out" bandpass and drops to 0.1 microvolt for normal filter settings — as good or better than most vacuum tube amplifiers.

OPERATION

Operator-oriented master controls provide separate record and playback adjustments for both "early" and "final" gain. Complete built-in amplifier test units make testing and control adjustments rapid and easy.

The PT-100 will provide you a new dimension in recording from refraction through normal reflection up to high frequency use. Phone or write for the COMPLETE brochure.

Every Shot Costs!

Why try to save pennies on doubtful recording supplies.

With the cost of each shot climbing every year, you can't afford to take chances—especially when the most you have to gain is pennies! SIE guarantees quality . . . quality controlled by a team that has been building its reputation with you for over 15 years.

Magnetic tape with higher output, better signal-to-noise ratio, and **guaranteed not to strip oxide in normal use**

Photographic supplies fresh-from-the-factory, laboratory tested, and on hand ready to go the same day your order is received

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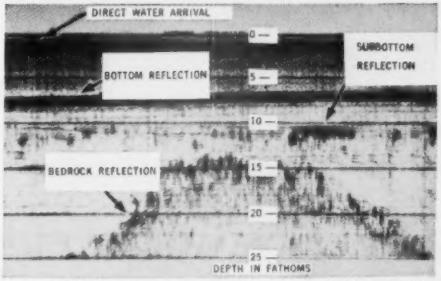

Representative reflection profile across irregular bedrock overlaid by several sediment layers — Narragansett Bay.

The broad tone shade response of **Alfax papers** and wide range of writing speeds of Alden "flying spot" **Helix Recorders** have been used to build an extremely flexible sonar recording and control instrument for the most rigorous all around high resolution deep sea recording. Designed by the scientists of Woods Hole Oceanographic Institute specifically for oceanographic research, the keying, record gating, drives and amplifiers chosen are now available in the **Alden #419 Precision Graphic Recorder**. Typical uses are:

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- **SCATTERING LAYER and BIOLOGICAL STUDIES**
- **BOTTOM MAPPING and HYDROGRAPHY**
- **SEISMIC PROFILING**
- **PRECISE TRACKING of LOWERED or TOWED VEHICLES**
- **SALVAGE, OCEAN MINING and CONSTRUCTION PROJECTS**

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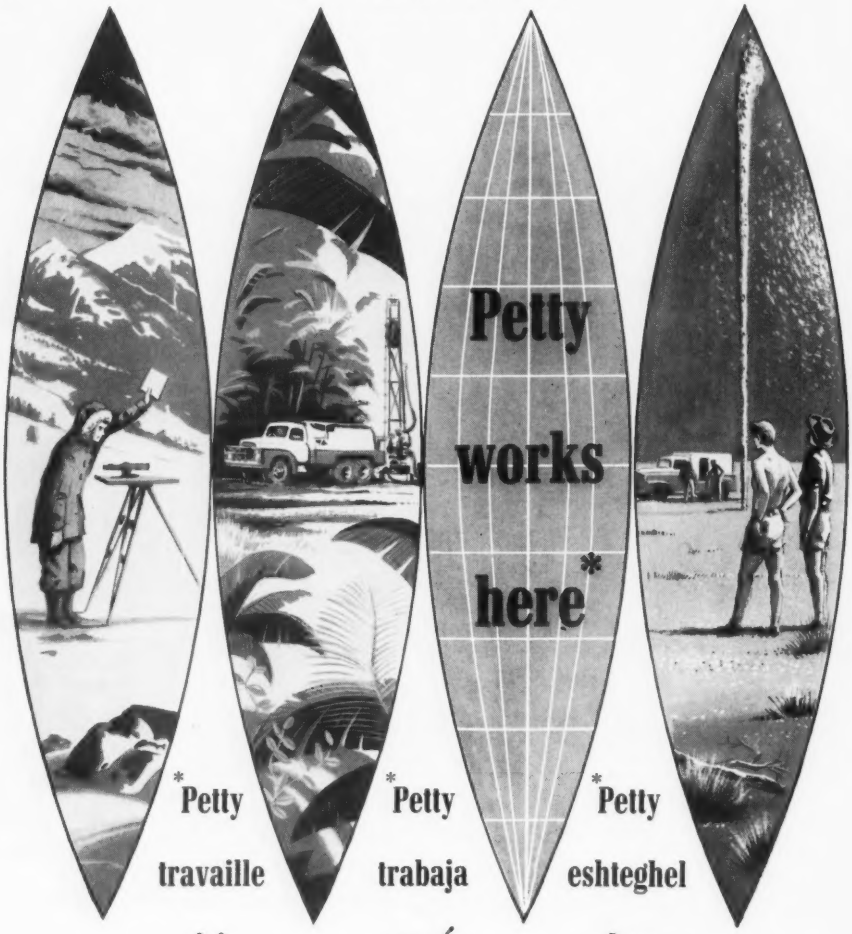
- **Alpine Geophysical Services** Houston, Texas, U. S. A.
- **Hunting Survey Corporation** Toronto, Ontario, Canada

ALDEN ELECTRONIC & IMPULSE RECORDING
EQUIPMENT CO., INC. Westboro, Mass.
Att: L. A. Farrington, Dept. E-1



Wherever geophysical research may be needed, the Petty patented* horizontal stacking technique will provide accurate subsurface surveys. Each subsurface point is verified by multiple ray paths, with only the reflection point common to all. Results: greatly reduced noise and maximum record clarity. Adequate supervision is granted from regional offices located in Brisbane, Queensland, Australia; Bogota, Colombia; Denver, Colorado; Lafayette, Louisiana; Irwin, Pennsylvania; and San Antonio, Texas.

*U.S. Patent No. 2,732,906

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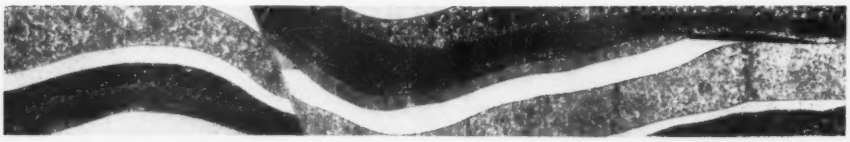

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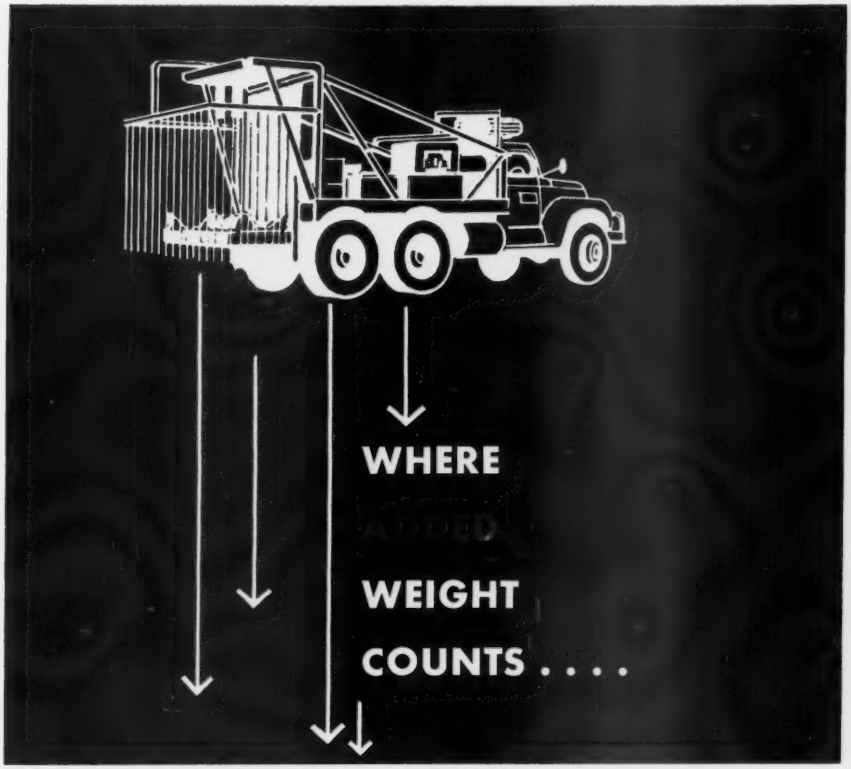

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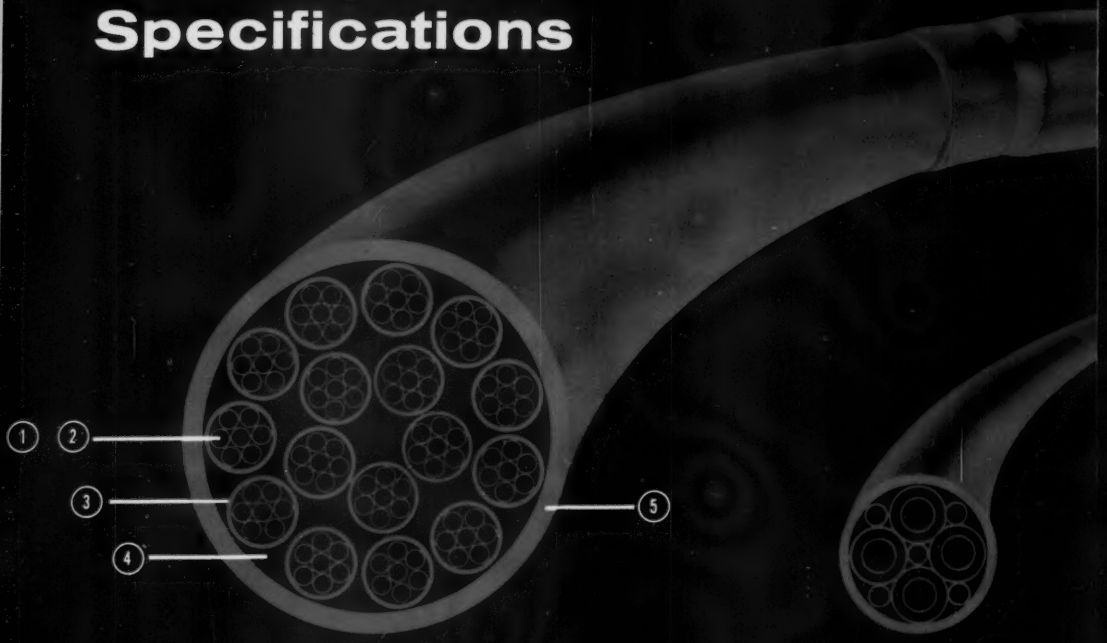

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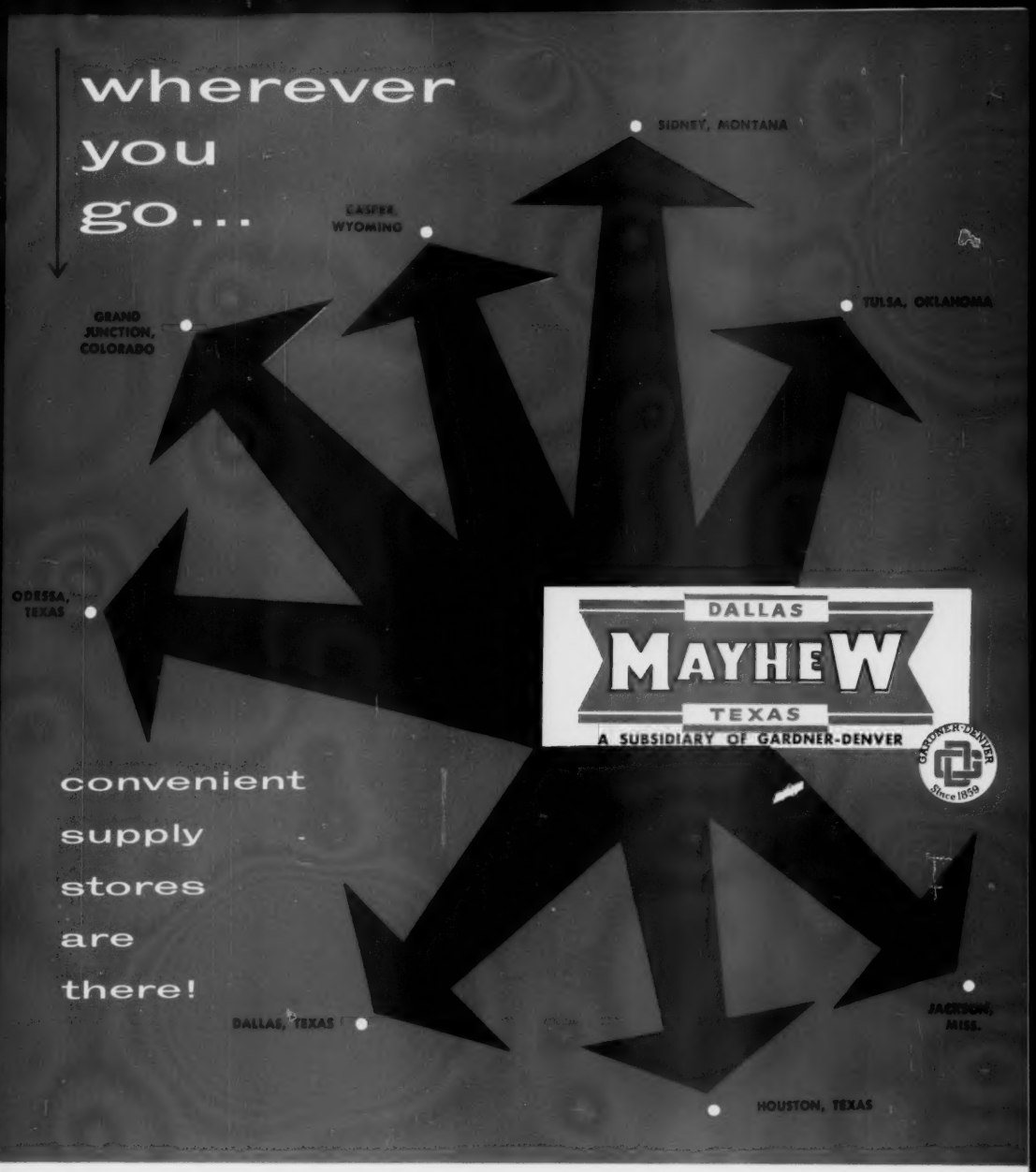

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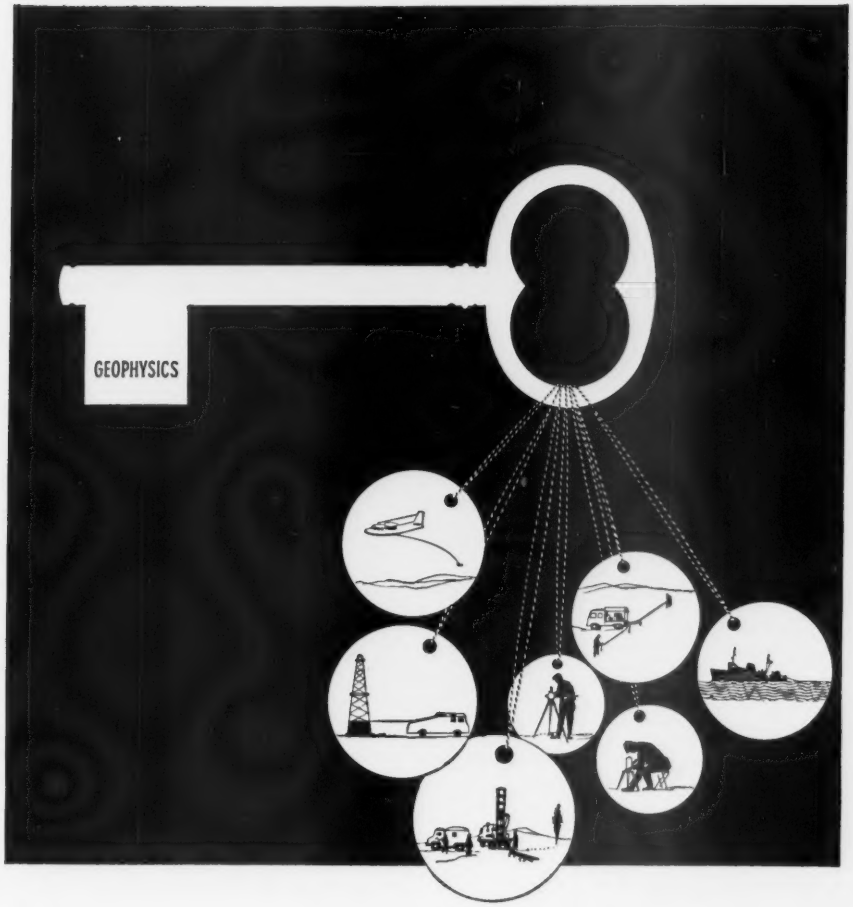

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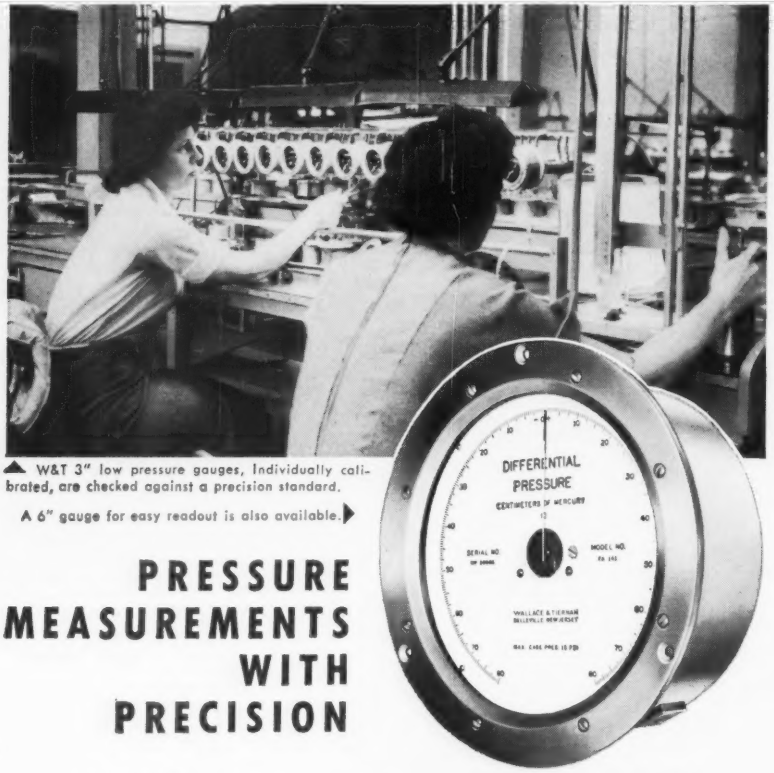

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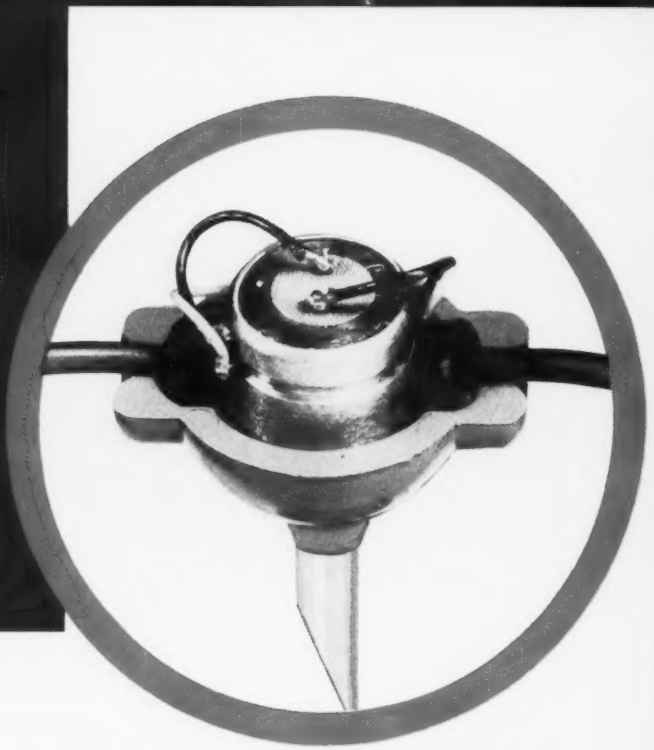
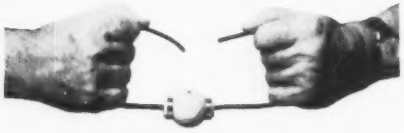


In Hall-Sears' new HS-J case, every geophone takeout has the full test strength of the cable



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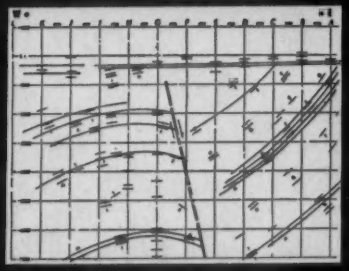

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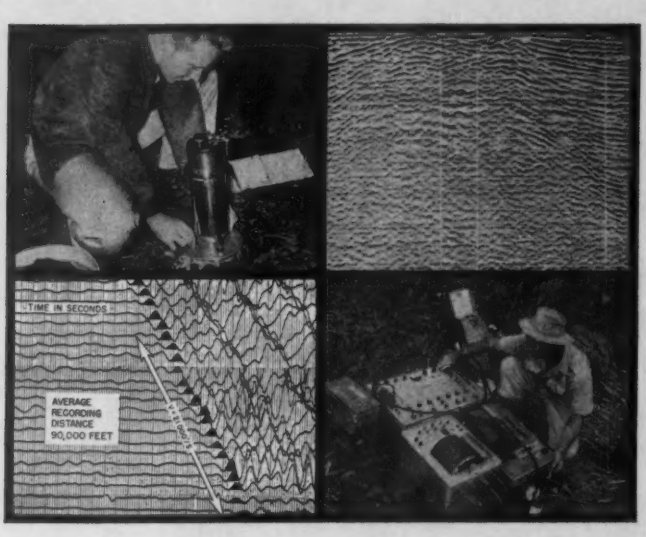

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